AMATEUR TELESCOPE MAKING ADVANCED

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Part I.

HAVING TO DO WITH THE CONSTRUCTION OF OPTICAL INSTRUMENTS

Backwoods Philosophy

By A. W. Everest
Pittsfield, Massachusetts

A PIECE OF GLASS

He labored late into the night,
At early morn' his task resumed,
To fashion thus a disk of glass
Into a subtle curve, not deep,
But measured only by the shades of light
From a simple pinhole made in foil,
Revealing to his practised eye
Imperfections infinitesimal;
Until at last his skill produced
A curve so true the mind of man
Could not discern the wavering of a breath.

"Just a piece of glass," 'twas said,
But in that simple disk
The heavenly host
Of suns and stars, yea, universes,
Revealed their glory in the sky
For man to ponder—and adore.

—C. A. Olson
Westwood, N. J.

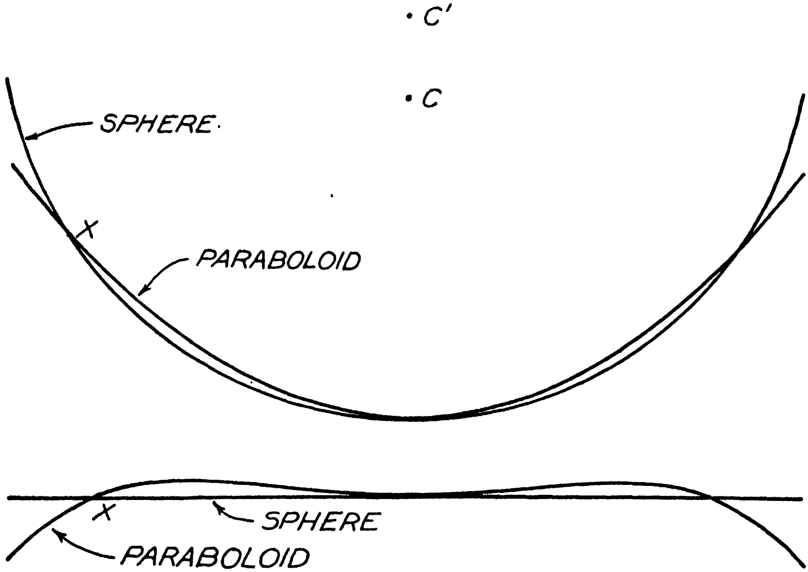
The first requirement in figuring a mirror is a clear conception of how it should appear on the testing stand, since it is by comparing what we see with what we ought to see that we determine what to do. This appearance, with the knife-edge in some intermediate position, has been said to resemble that of a doughnut—and the analogy is a good one, since, like amateur's mirrors, there are all kinds of doughnuts—rough ones, smooth ones, doughnuts with holes and doughnuts without 'em.

Well, what is the shape of the true paraboloidal doughnut? With Porter at the other end of the continent, about all we can do in the way of showing this three-dimensional appearance in two-dimensional space, is to draw its cross-section only, and leave it to the reader to visualize the surface of revolution this represents. The calculation of this cross-section is a simple matter. In fact, the cross-section of the paraboloid, as it appears with the knife-edge in any useful position, may be covered in a single equation. Let's figure the thing out under a heading somewhat in keeping with the method of calculation.

Doughnut Mathematics

For reasons which will become clear later on, the logical reference surface for our calculations will be a sphere whose center of curvature is at

the point of observation, *i.e.*, where the knife-edge cuts the cone of light. Further to simplify matters, this reference sphere may be made tangent to the paraboloid at its center, as in the upper part of Figure 1, making this point the origin of coordinates and thereby eliminating the constant of integration. In this example we have chosen a sphere whose center of curvature C prime is just outside of C, the center of curvature of the paraboloid's center zone. Starting at the center, such a sphere would lie outside the



All drawings by the author

FIGURE 1

paraboloid as far as some zone X, beyond which it would lie within. Viewed from its center of curvature, this reference sphere would appear flat, its apparent cross-section would be a straight line, and the apparent cross-section of the paraboloid would be a curve, somewhat as shown in the lower part of the same figure.

An expression for the deviation of the paraboloid from this or any other reference sphere will involve the following two propositions, which will be stated with a degree of accuracy equivalent to that of r^2/R without the tail end of the formula. This will permit the use of simple terms which will introduce no measurable error in the calculations for our telescope mirror; although, of course, the error would be intolerable in similar calculations for a large searchlight reflector.

Proposition 1: For the condition shown in Figure 2, the deviation of paraboloid from sphere varies as the fourth power of its radius r, and inversely as the cube of its radius of curvature R. In mathematical terms we would write,

$$y = -k\frac{x^4}{R^3} \quad (1)$$

The minus sign is inserted to indicate that the curve bends away from the observer. For the slope at any point, the first theorem in elementary calculus (about all we remember) tells us,

$$\frac{dy}{dx} = -4k\frac{x^3}{R^3} \quad (2)$$

Proposition 2: When observed from first one and then the other, of two points along the axis near the center of curvature, the slope of any

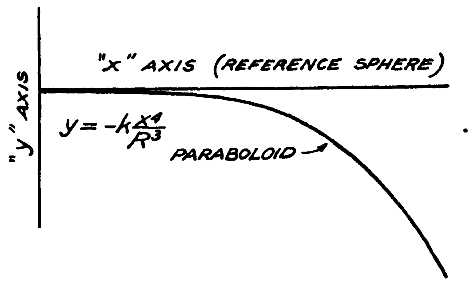


FIGURE 2

zone changes in proportion to the radius x of the zone, in proportion to the distance D between the two points of observation, and in inverse proportion to R. For the slope in one position compared with that in the other we may write,

$$\frac{dy}{dx} = KD\frac{x}{R} \quad (3)$$

whence,

$$y = KD\frac{x^2}{2R} \quad (4)$$

A useful example of this would be a spherical mirror examined first from its center of curvature, when it would appear flat and its apparent cross-section would be the straight line shown in Figure 3. If now the knife-edge be moved a short distance D toward the observer, the surface will appear concave, y varying in proportion to x^2 as shown.

We may now investigate what would happen to the curve shown in Figure 2 if the knife-edge is moved toward the observer. The slope of each zone would change in accordance with the law given in the preceding paragraph, which means that certain sets of y values determined by Prop. 2 would be added to those determined by Prop. 1. For example, Figure 4 shows the re-

sult of adding the actual y values of Figure 3 to those of Figure 2. As a useful proposition, however, the mere addition of the right-hand members of equations (1) and (4), giving

$$y = KD\frac{x^2}{2R} - k\frac{x^4}{R^3} \tag{5}$$

would mean nothing until we express K in terms of k. To do this we may consider that y is to reach its plus maximum at the point where the curve, such as the one shown in Figure 1, at bottom, or the one shown in Figure 4, becomes flat at the crest. This will be when the slopes represented by the

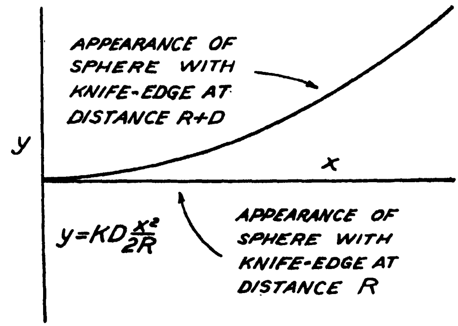


FIGURE 3

$\frac{dy}{dx}$ values of Propositions 1 and 2 cancel each other, *i.e.*, where

$$KD\frac{x}{R} - 4k\frac{x^3}{R^3} = O$$

whence, $$K = 4k\frac{x^2}{DR^2} \tag{6}$$

For this point in the curve, $D = \frac{x^2}{R}$

Substituting this value of D in equation (6),

$$K = 4\frac{k}{R}$$

and substituting this value of K in equation (5),

$$y = 2kD\frac{x^2}{R^2} - k\frac{x^4}{R^3}$$

whence, $$y = k\frac{x^2}{R^2}\left(2D - \frac{x^2}{R}\right) \tag{7}$$

where D is the distance of the knife-edge from the center of curvature of the center zone. For the actual deviation of paraboloid from reference sphere, k would be 0.125, and the whole expression would represent an amount too small to be seen. *But*—

The combination of tin can and razor blade forms a telescope magnifying, roughly, *one hundred thousand times;* the exact amount varying directly with the focal length and depending somewhat upon the sensitivity of the arrangement and individual interpretation. The amount stated is about right for an $f/8$, 10″ mirror, based on the opinions of a number of experienced amateurs, using the testing arrangement to be described. Any error here is

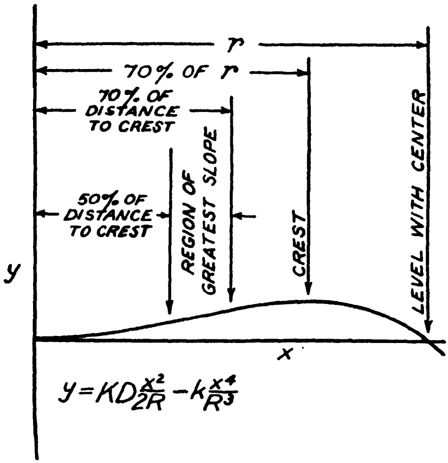


FIGURE 4

immaterial, since it will have no effect whatsoever upon the characteristics of the curve which are to be considered.

Compared with the more familiar telescope, this one has the peculiarity that its tremendous magnification is in *depth only,* that is, the mirror is seen with actual diameter, but with every deviation from reference sphere magnified by the above amount. For example, our 10″ paraboloid, examined with this apparatus from the center of curvature of the center zone, appears to deviate about 2″ from flatness at the marginal zone, although in reality this deviation is only about 20 millionths of an inch. Likewise, the apparent deviations of all intermediate zones bear the same relation to the real.

Assuming a magnification of 100,000, or 625R, to be correct for the 10″ mirror, k becomes about 80R, and equation (7) changes to,

$$y = 80\frac{x^2}{R}\left(2D - \frac{x^2}{R}\right)$$

This is our final "Equation of the Doughnut," from which the values of y may be stated in terms of the markings on a 6″ scale.

Selecting values of D from zero to r^2/R in 10 percent steps, we may calculate coordinates for our 10″ mirror and then put these in curve form, as shown in Figure 5. The top curve shows the apparent cross-section of the mirror as it should appear with the knife-edge at the center of curvature of the center zone. The bottom curve shows how it should appear with the knife-edge at the center of curvature of the marginal zone. The heavy curve

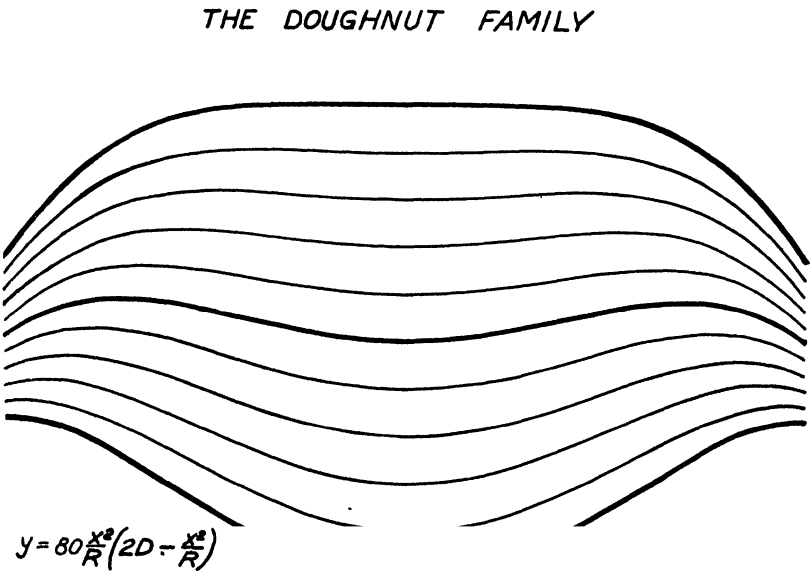


FIGURE 5

half way down shows how it should appear with the knife-edge exactly half way between the above two positions. We call this the "half-way" or 50 percent curve. Starting at the top, the light curves drawn in between the three heavy ones represent the apparent cross-sections corresponding to knife-edge positions of 10, 20, 30, 40, and 60, 70, 80 and 90 percent of r^2/R.

The curves have been drawn with sufficient accuracy to bring out their fixed characteristics, that is, those landmarks which remain unchanged regardless of the values of k, r, or R we may select.

First, note that all the curves are *smooth*. There is no sudden change in slope at any point. Next, starting with the top curve and examining the whole series in order, note how the crest spreads from center to end; in large

jumps for the first step or two, and then with smaller and smaller hops with each succeeding curve. A simple transposition of the r^2/R formula tells us that the location of the crest should be as follows.

Knife-edge position	*Location of crest*
00 percent of r^2/R	Center
10 " " "	31.6 percent of "r"
20 " " "	44.7 " " "
30 " " "	54.8 " " "
40 " " "	63.3 " " "
50 " " "	70.7 " " "
60 " " "	77.5 " " "
70 " " "	83.7 " " "
80 " " "	89.5 " " "
90 " " "	94.9 " " "
100 " " "	100.0 " " "

A trial with straightedge and scale will show the curves to be in agreement with the above. Note, however, the flatness of crests near the center and the resulting difficulty of determining their exact location compared with those farther out. Note especially the flatness of the crest in the first curve which, of course, is at the center of the mirror. Pay particular attention to the distance this flatness extends from the center before there is any perceptible deviation from a straight line.

Now try to locate the regions of greatest slope in the central depressions, *i.e.*, where the curves reverse. This will be more difficult to decide, and impossible with the first two or three curves. But, as nearly as can be judged, these regions of greatest slope will be found to extend from 50 percent to 70 percent of the distance from center to crest for any of the curves. A solution for the maximum plus value of the expression $\frac{dy}{dx} = 4k\frac{x^2}{R^2}\left(D - \frac{x^2}{R}\right)$ [derived from equations (2) and (3)], would show an intermediate point of slightly greater slope than the rest. But let's not introduce this typesetter's nightmare into the discussion, as no difference could possibly be detected by visual inspection. We are interested only in the practical result, which is shown in Figure 4 and will be discussed in more detail later on.

Other landmarks:

The depth at the end of the first curve is the same as the depth at the center of the last one.

The depth of the half-way curve is one-quarter of the above.

The center and end of the half-way curve are of the same depth, and this is the only curve for which this is true.

In the 70 percent curve (the eighth one down), the greatest slope in the central depression is the same as that at the end.

There is *only one shape of doughnut,* just as there is only one *shape* of

parabola. This is shown in Figure 6, where we have superimposed the half-way curves for three paraboloids of the same diameter but different focal ratios. All have exactly the same characteristics in regard to the relation between progressive values of y and dy/dx. The only difference is in the intensity of the "bulge."

A glance at the doughnut family will show how the intensity of curvature varies far out of proportion to the diameter of the mirror. For any of the curves after the first one, the portion inside the crests may be used to represent the 100 percent curve for a mirror of that diameter. For the second curve, this diameter would be 31.6 percent of the last one, but the depth is hardly discernible in comparison—actually 1 percent.

And now that we have completed some painful reasoning, let's proceed to

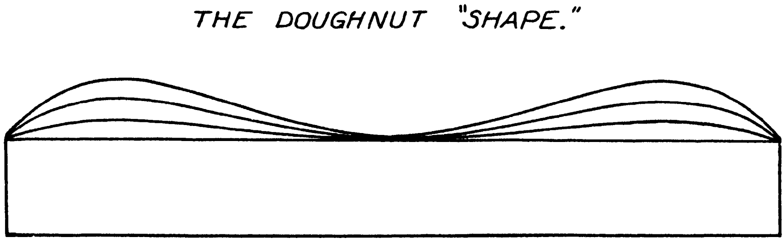


FIGURE 6

forget it and just form a clear mental picture of the curves, especially the three heavy ones, and the surfaces of revolution they represent. The squared background of the graph paper on which the curves were originally drawn has been purposely omitted from the reproductions, since there will be no such thing to guide us in the knife-edge test. Outside of a few zonal measurements, when figuring our shallow mirrors, we must be guided entirely by appearance, in deciding when the goal has been reached.

SHADOW BEHAVIOR

In speaking of a shadow, we refer to the *division between light and shade,* not to a whole *area* of shade. In locating a shadow, we refer to the point where it crosses the horizontal diameter of the mirror, since this is the point where any measurement will be taken. An area of shade which does not extend to the rim of the mirror will, of course, be surrounded by one continuous shadow; but since this shadow will cross the horizontal diameter at two different points, we shall speak of this area as bounded by *two* shadows, one on the left and one on the right.

If we imagine the mirror to be divided in half vertically, zones which have any appreciable slope will be illuminated in one half and dark in the other, when the knife-edge is in the correct position to bring out the grazing

incidence effect. In Figure 7, for example, the outer zone will be illuminated in the right half and dark in the left. In the central zone the illumination will be just the reverse. In this illustration we see three shadows as defined above which, for reference purposes, will be numbered 1, 2 and 3, as shown.

It is evident from the law of reflection that shadows will move in the

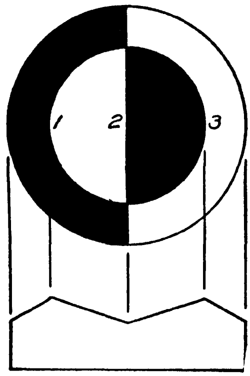


FIGURE 7

same direction as the knife-edge in zones which appear convex toward the observer, and in the opposite direction in zones which appear concave. In Figure 8, at left, the mirror is convex from center to rim, in spite of the fact that it has a central depression. Therefore, shadows 1 and 3 would move in the same direction as the knife-edge across their respective halves of the

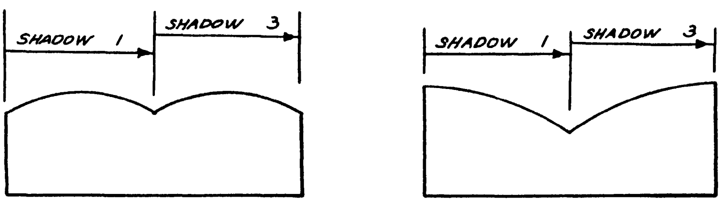


FIGURE 8

mirror. (Shadow 2 in this case would remain stationary at the center.) In Figure 8, at right, which represents the same surface as it would appear with the knife-edge just outside the center of curvature of the marginal zone, the shadows would still move in the same direction. For the zone inside the crest in Figure 8, left, and for the whole surface in Figure 8, right, the direction in which the shadows move contradicts the old rule that "the shadow will move in the opposite direction when the knife-edge is outside

the center of curvature." Strictly speaking, this rule applies to spherical mirrors alone, and, for general application, should be restated as at the beginning of this paragraph.

Assuming a uniform speed of the knife-edge as it cuts through the cone

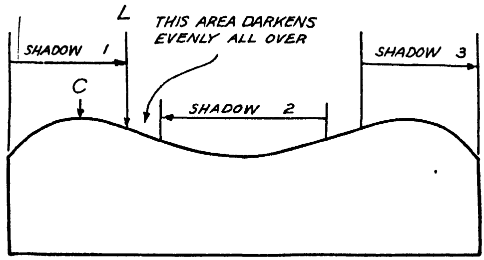


FIGURE 9

of light, the speed of a shadow will be an inverse function of the rate of change of slope. In other words, the shadow will move slowly across zones of pronounced curvature, and comparatively fast across zones having little change in slope. In Figure 9, shadow 1 would move slowly to the crest and

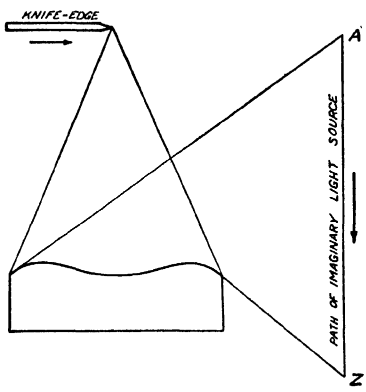


FIGURE 10

then move faster and faster as it approached *L*, where the curve flattens out at the beginning of the zone of greatest slope in the central depression.

In zones where there is no change in apparent slope with a given knife-edge setting, there will be no shadow motion. Such zones will darken evenly all over. Referring back to Figure 4, we see that, in the true paraboloidal figure, such a zone always exists in the central depression extending from

about 50 percent to 70 percent of the distance from center to crest. We are particularly interested in the 70 percent point, *L*, which we may call "the shadow limit," since this is the point beyond which no motion of shadow 1 can be detected. Picking up this shadow again from where we left off in the preceding paragraph, when it reaches the shadow limit, the zone of

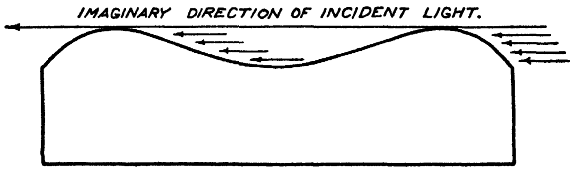


FIGURE 11

greatest slope will have just finished darkening, and the two effects will blend in with each other. During all this procedure, shadow 2 will have been approaching shadow 1 across the concave part of the central depression and will blend in about the same manner, except, of course, from the opposite direction.

In interpreting shadows, we imagine them to be caused by the light source being off somewhere to the right of the mirror rather than by the knife-edge shutting off the light. For a shadow to exist under this condition, it follows that the incident light path must be imagined to be tangent

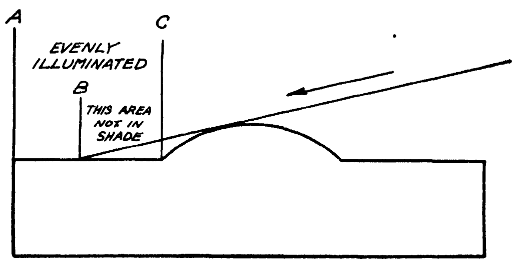


FIGURE 12

to the surface at the point where the shadow happens to be. And, since shadows move as discussed above, it follows again that the light source must be imagined as moving away from the observer in a direction parallel to the axis of the mirror. In Figure 10, from the time when shadow 1 enters the left side of the mirror until the time shadow 3 disappears off the right, the light source must be imagined to have traveled from *A* to *Z*.

Bumps, raised zones, etc., will not cast shadows on adjoining parts of the mirror. This is due, of course, to the fact that the actual direction of the light path is parallel to the axis of the mirror. In Figure 11, when the

apparent direction of the light path is at right angles to the mirror's axis, the right crest will not shut off the light from the left side of the central depression, but this area will be illuminated as shown by the arrows. In the case of a bump in the center, as in Figure 12, when the light path appears to be in the direction shown, the left side of the bump will be darkened, but not the area from *B* to *C*, as would be the case if the light were actually coming from that direction. This area will have the same illumination as from *A* to *B*. This fact must be remembered when locating the left boundary of a bump or raised zone. Otherwise, being accustomed to seeing light behave in the more familiar manner, the mind's eye will unconsciously place the left boundary of the protuberance somewhere within the area of shade, rather than at the left edge of this area where it belongs.

The Error of Observation

If we are using the stop method of testing a zone, both exposed arcs will darken at the same time when the knife-edge is at the center of curvature of this zone. If the stop is removed, the apparent crest, or greatest bulge toward the observer, will be located at this zone. If we are watching shadows 1 and 3 move across the mirror, both will reach their respective crests at the same instant. Assuming, for graphical purposes, that the knife-edge

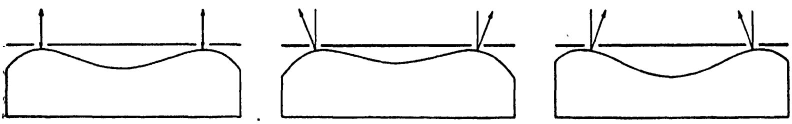


Figure 13

and slit are at the same point, the light striking this zone will be reflected back along the incident path, as shown by the arrows in Figure 13, left.

If the knife-edge is slightly nearer the mirror, we can see from the slopes in Figure 13, center, that, with the stop, the left arc will darken before the right. Without the stop, the crest will appear nearer the center, and shadow 1 will reach the zone before shadow 3. If the knife-edge is slightly farther away, as in Figure 13, right, all these effects will be reversed.

So much for theory. In actual practice, however, we know that in making any fine measurement there is always the possibility of a residual error due to the limitations of the measuring device and, perhaps, to the human element involved. To get some idea of what this might amount to in the knife-edge test, the group of amateurs mentioned above tested the $f/8$, 10″ mirror, first using a stop having ¼″ arc-shaped openings at the zone of 4″ radius, to determine just how far the knife-edge could be moved along the axis and still have both arcs appear to darken at the same time; or, to put it another way, the minimum movement of knife-edge before the transition from Figure 13, center, to Figure 13, right, could be detected. The average result was the rather large quantity of .02″, with the individual readings

surprisingly consistent. All stated that the diffraction around the arcs had a blinding effect on what they were trying to see. Hence, the stop was replaced with a quarter-inch strip of wood across the horizontal diameter of the mirror, with two short pieces of pin driven into the stick to indicate the exact location of the zone. The test this time was to see how far the knife-edge could be moved and still have shadows 1 and 3 appear to reach their respective pins at the same instant. The average immediately came down to slightly less than .01″, the main difficulty this time being to decide just where, in the mass of spiderwebs between light and dark, the shadow should be interpreted to be.

The next test was on the center zone, first using a stop with a 2″ hole, and then removing the stop and testing for the appearance represented by the first curve in the doughnut family; that is, with neither a bump nor a dimple in the center of the mirror. This time the results were about the same for either method, the diffraction at the circumference of the opening not bothering due to the larger area of the mirror's surface exposed. The

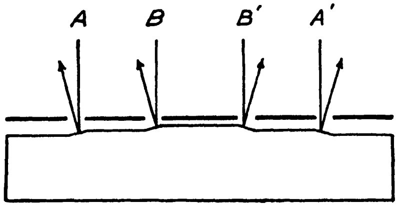


FIGURE 14

knife-edge could be moved about .04″ without detecting any motion of the shadow when using the stop, or seeing any deviation from apparent flatness at the center without the stop.

In these tests, we were sneaking up from both sides, so to speak, so that the maximum displacement of knife-edge from the correct position would be about half the amount stated for either zone. It is also reasonable to assume that, in taking the average of a number of readings for a zone, or taking the mean of the two measurements giving the transition from Figure 13, center to Figure 13, right, we could cut these amounts in half once again. Let's go ahead on this basis, using .0025″ as the error of observation for the 4″ zone, and .01″ as the error for the 1″ zone.

The factor which determines the interval of time between the darkening of the two sides of a zone, that is, the ease with which this can be detected, is the dy/dx value of the slope. This can be seen in Figure 14, where there are two zones A-A' and B-B', of different radius, but having the same slope. A and B will darken at the same time, as will A' and B', when the knife-edge is farther advanced. Therefore, the interval between the darkening of the two sides will be the same for either zone. Assuming the slope of one zone to be just sufficient to detect this difference in time of darkening of

the two sides, the same will hold true for the other. In other words, the error of observation involves a minute fixed value of slope, regardless of the radius of the zone. We saw in Doughnut Mathematics, Prop. 2, that any change in slope of a zone, resulting from a movement of the knife-edge along the axis, was represented by the expression $\frac{dy}{dx} = KD\frac{x}{R}$. And since, here, dy/dx has a fixed value, as stated above, we may combine the constants and rewrite the expression, $K = D\frac{x}{R}$ whence, $D = K\frac{R}{x}$. (8)

Figure 15 shows another way to approach the problem. Here we have two mirrors of different focal length, but the same focal point f, being tested

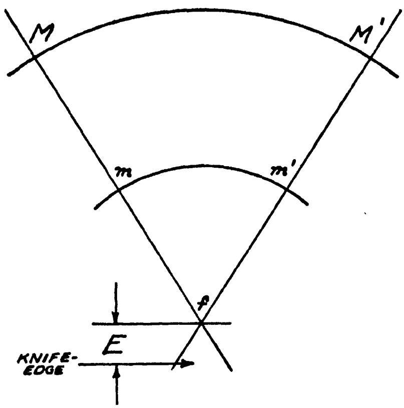


FIGURE 15

for zones M-M' and m-m' of the same aperture ratio, R/r. If the knife-edge cuts through the cone of light at some distance E from f, but just close enough so that no difference in the time of darkening of M and M' can be detected, the same will hold true for m and m'. In other words, the error of observation is a direct function of the focal ratio, for which we may write, $E = k\frac{R}{r}$. This, of course, is the same thing as equation (8) with a change of characters. Solving for k, by using the value of E determined for either the 1″ or the 4″ zone of the 10″ mirror, the equation for the error of observation becomes,

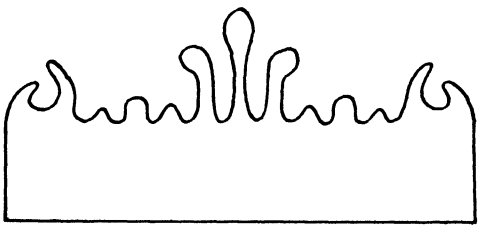
$$E = .00006\frac{R}{r}. \tag{9}$$

ACCURACY OF THE KNIFE-EDGE TEST

The answer to the question, "How accurate is the knife-edge test?" depends upon which class of errors is under consideration—those which can be measured but not seen, or those which can be seen but not measured. Strange as it may sound, the latter can be detected much the closer of the two, in terms of thickness of glass to be removed.

Referring back to Figure 6, and assuming that the three curves represent different intensities of figure on one and the same mirror, it would be impossible to tell from visual inspection under the knife-edge test, which one was correct. Zonal measurement for radius of curvature would be required. In Figure 16, however, such measurement would be impossible; it would be necessary to estimate the intensity of these various protuberances by visual inspection alone.

The measurable errors, then, are those in over-all correction, and the



(APOLOGIES TO UNK)

FIGURE 16

accuracy obtained depends upon the zones selected for test. Theoretically, the exact center of a mirror cannot be tested for radius of curvature. Also, the extreme marginal zone is difficult to read, owing to the diffraction at the edge; or if a diffraction edge is missing, the glaring illumination of the turned edge at the right is a worse source of trouble. So, in practice, it is better to select knife-edge positions of, say, 10 percent and 90 percent of r^2/R, bringing the zones to be tested at 32 percent and 95 percent of r, as shown in the tabulation on page 9. Although the ease of reading the difference in knife-edge positions will be reduced 20 percent, this will be offset many times by the gain in sensitivity and reduction in the error of observation. There are better ways than zonal measurement to tell when the curve is true right in to the center, or out to the extreme edge.

In the following tabulation, $.00006R/r$ has been calculated for the 32 percent and 95 percent zones for three different mirrors, and since it is probable that the error would be made in one direction for one zone and in the other direction for the other, the two values have been *added together* to get the total error in over-all correction which might be made.

(Note: Your mentor confesses the responsibility for Figure 16, the result of early experiments with HCF strips.)

	80 percent of r^2/R	knife-edge error	percent error	$r^4/8R^3$	error in millionths of an inch
$f/8$ 6″	.075″	.008″	10.7	.0000114″	1.2
$f/8$ 10″	.125″	.008″	6.4	.0000191″	1.2
$f/5$ 10″	.200″	.005″	2.5	.0000781″	2.0

The above shows that measurements down to 1 millionth of an inch in thickness cannot be made with any degree of certainty. But it will be seen, by referring to "Accuracy in Parabolising," in "A.T.M.," that the probable error of observation is well within the tolerance given—all of which means that, if a mirror is figured to this degree of accuracy, brilliant performance may be expected, provided the numerous other conditions necessary for this performance are correct.

The other class of errors includes close zonal irregularities, dog-biscuit, lemon peel, bumps, etc. One illustration with the 10″ mirror will serve to

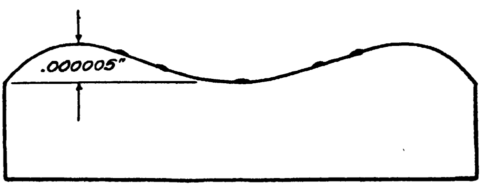


FIGURE 17

show how closely the thickness of these protuberances may be estimated by visual inspection, although it is impossible actually to measure it. Figure 17 shows the apparent cross-section with the knife-edge at the half-way position, bringing the crest at 70 percent of the distance from center to rim. Referring to page 9, it will be seen that the deviation of this crest from the reference sphere is one quarter of $r^4/8R^3$, or about 5 millionths of an inch. Several slight protuberances have been placed on the curve, having a depth of $\frac{1}{20}$ of this amount, or one quarter of 1 millionth of an inch. These could most certainly be seen with a sensitive slit.

Testing Equipment

Let this be simple but substantial. Micrometer screws are unnecessary, and if the outfit is mounted on anything less rigid than a solid concrete foundation, they are useless. If the mirror and knife-edge are mounted on separate supports, a slight pressure of the finger tips on the side of the bench holding the knife-edge will give more sensitive control of the shadows than any micrometer arrangement the amateur will be likely to make. The only care necessary is to see that this pressure will result in motion at right angles to the mirror's axis alone. And the more solid the bench, the better this will work.

If there are any perceptible air currents between the knife-edge and mirror, a testing tunnel will be required for close reading. This may be a simple wooden framework covered with heavy cloth, and having a cross-section about 50 percent greater than the diameter of the mirror. The cloth may hang down at one side, in the form of a flap which may be raised to insert the mirror.

Provide the mirror support with some means of adjusting to bring the light rays back to the proper point when the mirror is in position. Three wooden wedges will serve the purpose. After the adjustment is once made, screw or clamp the support to the bench. If the front and back of the mirror are not parallel, paint an index mark on the edge, and always have

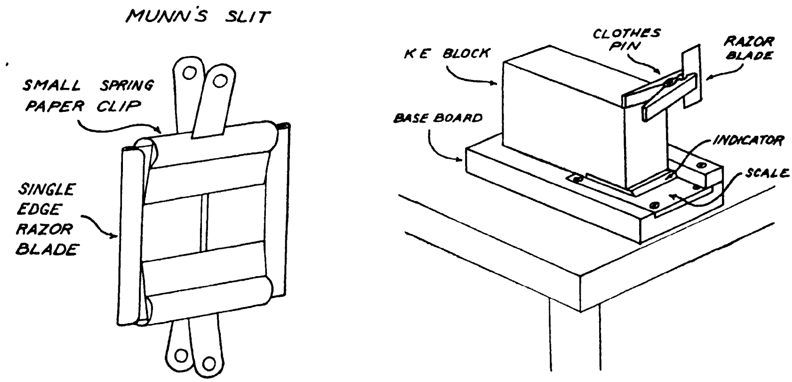


FIGURE 18

this mark in the same position when the mirror is on the rack. The above will save time getting lined up for those frequent tests during the final stages of figuring.

The light source may be a an inside-frosted incandescent lamp bulb inside a small tooth powder can, in one side of which a 3/8" square or circular opening has been made.

The slit may be two safety razor blades clipped between two spring paper clips, as shown in Figure 18, at left, with the opening between the blades set to about the thickness of ten sheets of typewriter paper. An extremely narrow slit is not advisable when used with the knife-edge, due to the diffraction effects which result. Sensitivity depends on parallelism of knife-edge and slit. True, when the mirror is just beginning to darken, there will be a marked reduction in contrast between light and shade with the wide slit, making the over-all shape much easier to see or photograph. But the actual shadow, as defined above, will be as sharply defined as if produced by an infinitely narrow slit. In fact it *is* produced by just such a narrow strip of light, bounded on one side by the right edge of the image

of the slit and on the other side by the knife-edge itself. For the same reason, the wide slit will be just as effective as the narrow one in detecting close zonal irregularities just before the mirror completely darkens. And for comparative freedom from diffraction effects in the vicinity of the shadow, the wide slit is easily the choice. Also the rectangular aperture of the slit is the only light source which will illuminate the various zones of the mirror in direct proportion to their slopes, giving the correct appearance to the curve. It is essential that knife-edge and slit both be at right angles to the axis, otherwise a marked reduction in sensitivity will result.

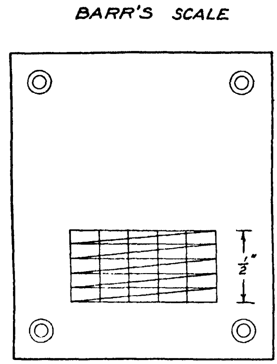


FIGURE 19

Remember that the pupil of the eye is well dilated when testing and takes in considerable of the knife-edge and image of the slit.

For Ronchi testing, the slit must be closed down to the thickness of one or two sheets of paper. For example, if gasolene screen is used for the grating, the slit must be somewhat narrower than the thickness of the wires in the screen, to get good definition of the lines.

For quick exchange from razor blade to screen, a spring clothes pin may be cemented to one end of the knife-edge block, as shown in Figure 18, at right. This will also permit rotation of either one around the mirror's axis, to get parallelism with the slit. To get the knife-edge parallel, push it about 1" inside the center of curvature, bring the shadow in to the center of the mirror, and then rotate the knife-edge one way or the other until the point is found where the shadow doesn't move sidewise when the head is bobbed up and down. With the Ronchi grating, do the same thing until the lines will stand still. The recommended length of slit, or even longer, will be found a decided advantage in getting accurate parallelism by this simple method.

The knife-edge block should slide freely on its base board. It is rather difficult to construct parallel ways for the block to slide between with the necessary freedom, so it is better for the amateur's purpose to provide just

one cleat, as shown in the illustration, using a little side pressure when moving the block, in order to keep it against this cleat.

The measuring devices will include a scale on the knife-edge base board, and a measuring stick hung across the horizontal diameter of the mirror. The scale we prefer, because of its simplicity and ease of reading, is shown in Figure 19. This is a flat plate of brass screwed to the base board, with parallel cross lines at tenth-inch intervals, and diagonal and vertical lines as shown; all accurately scribed with a fine, sharp engraver's tool. The indicator is another piece of brass screwed to the under side of the knife-edge block, as shown in Figure 18. With this device, the nearest half of a hundredth inch may be easily seen, which is about as accurately as we may expect to read. The measuring stick is a quarter-inch-square stick of wood with a loop of wire to hang it across the horizontal diameter of the mirror, as shown in Figure 20. Our preference for the spacing of the pins is to

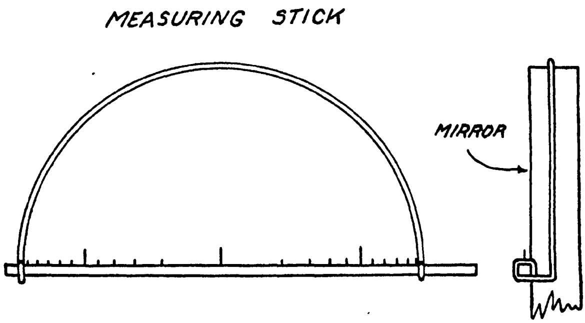


FIGURE 20

locate the zones given in the table on page 9, those at the center and at the 70 percent points being slightly longer than the rest. Others, depending upon how their mental processes work, may prefer to place them at ½″ intervals.

For the reasons given in "The Error of Observation," stops are taboo for testing parabolic mirrors in at least one outfit we can name. They are used only for finishing spherical mirrors and flats, where shadows are lacking to test both sides of a zone. And we are not so sure that even here we cannot see all there is to see without them on small surfaces. When used, the openings are made 1″ wide.

Testing

The tests for a true parabolic curve will include the following routine.

1. Look for the diffraction effect at the edge, as explained in "A.T.M." Theoretically, the left edge should be as bright as the right, but in practice this will seldom be obtained. However, a clean hair-line of light should

follow the left edge of the mirror, and the illumination at the right side should not persist to any noticeable extent longer than the diffraction around the edges of a screw driver or similar object placed vertically before the mirror.

2. Inspect the surface as a whole for zonal irregularities, that bumpiness called dog-biscuit, lemon peel, etc. If these are absent and the surface appears velvety smooth, it has what Unk calls "schoolmarm's leg," or in more highbrow terms, it is an *optical surface*.

3. Set the knife-edge at the 90 percent position on the scale, and then slide the whole assembly including the base board along the bench until the point is found where shadows 1 and 3 reach the 95 percent zones together. Here is where the value of the recommended spacing of the pins on the measuring stick will be seen—they leave nothing to guesswork. Take a squint along the side of the cleat to see that it is pointing at the center of the mirror, since this is the key setting for the whole test. If accurately lined up, the knife-edge may be pushed toward the mirror, causing the crest to roll in toward the center without the illumination otherwise dying out, or the mirror becoming wholly illuminated. After making any adjustment necessary to produce this effect, check the 90 percent position against the 95 percent zone once more and then leave the base board in this position. Before leaving this zone, check the shadow limit, which should be at 70 percent of the 95 percent. No guiding pin will be found here, but the point may be estimated closely enough from the pins at either side. And don't forget that homely method of pushing lightly on one side or the other of the bench to bring the shadows exactly where wanted. Also decide right here what you are going to *call* the shadow; probably the point where none of the remaining spiderwebs of light cross the pin.

4. Push the knife-edge in to the 50 percent position and test as above on the 70 percent zone, first seeing that shadows 1 and 3 reach their respective pins at the same time, and then that the shadow limit for shadow 1 is half way from center to rim. Also note, while the mirror is only partially darkened, that the *depth* at the center appears to be the same as that at the rim.

5. Push the knife-edge to the 10 percent position and test the 32 percent zone. This time there will be some difficulty in determining just when the shadows reach their respective pins, due to the flatness of the crest. The general appearance of the whole central area of the mirror must be taken into consideration, based on the 10 percent curve of the doughnut family. There should be just a slight resemblance of a depression inside the zone, coming to a crest at the 32 percent point, as nearly as can be decided. If no slope can be detected one way or the other at this zone, it will never scatter light in a star image.

6. Push the knife-edge to the zero position. The last trace of a central depression should just disappear without raising any resemblance of a bump at the center. In other words, the whole central area should appear *flat*. See the first curve in the Doughnut Family.

7. Push the knife-edge ½" past the zero position and bring the shadow

half way in from the left edge to center. The shadow should have a slight but smooth curve inward, and run off the edge clean, with no change in curvature. If it bends inward at the edge, the edge is turned. If it straightens out or bends outward, the edge is undercorrected or turned up. All this, of course is a simplification of the Ronchi test. But it tells the whole story as far as the edge and marginal zone is concerned.

8. Bring the knife-edge back to the 70 percent position, with the crest at 84 percent of r. As can be seen from the note on this curve, page 9, shadow 1 should just be entering at the left edge of the mirror when shadow 3 is breaking out in the right side of the central depression. Also, shadow 1 should reach the shadow limit when shadow 3 is just passing off the right side of the mirror.

With a little experience, all of the above tests may be made in a few minutes, and, in our opinion, a mirror which passes them may be rated 100 percent. We believe the so-called personal equation associated with stop testing is due mainly to the blinding effects of diffraction around the open-

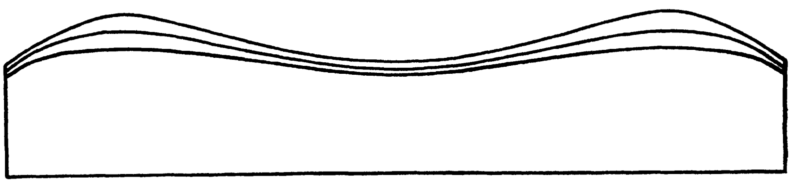


FIGURE 21

ings, and to the necessity of seeing something happen at two different places at one time. These troubles are not present with crest reading. The diffraction at the pins is just sufficient to enable them to be readily seen. Shadow 1 is brought to its pin and *stopped there,* so that we may take all the time we wish, to see whether shadow 3 has just reached the correct point. If both are where they belong for the various settings of the knife-edge, they just can't be anywhere else—that is, within the limits of the error of observation.

By now we can see the advantages of testing in equal steps of knife-edge position rather than in equal steps of the radius of the mirror. Each zone may be measured with the same degree of certainty, and all are of equal importance, since each involves the same area of the mirror.

Well, we have tested a good mirror. Let's test some of the others. If a mirror has the true paraboloidal appearance but, with the knife-edge settings mentioned above, the crests are not found in the correct location, the inference is obvious. If the crests are too close together, the mirror is overcorrected, and vise versa.

For irregular surfaces, such as represented by the upper and lower curves in Figure 21, the three zonal measurements would not tell the story. The center curve is the only correct one, yet it is evident from the slopes of the center, 70 percent, and marginal zones, that any one of them would test

the same for all three mirrors, and if these were the only tests made, any one of the three mirrors would be pronounced correct. Yet it is obvious that the upper curve represents about 50 percent over-correction, and the lower one about the same amount under. While it is true that the light reflected from these three zones could be brought to a focus, the waves arriving from the 70 percent zone would be somewhat out of phase with those from the other two zones, resulting in an actual *loss* of light. The best means of detecting these errors will depend on the size of the mirror

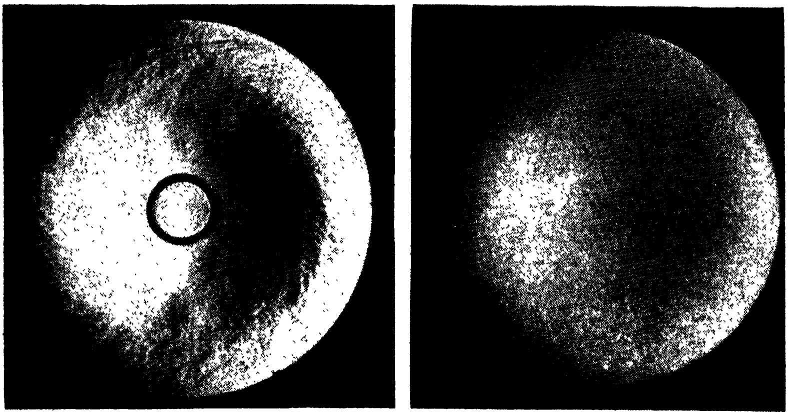


FIGURE 22

(The mirror on the left was not made by the technic described in this chapter, or by its author, but the one on the right was made in its entirety by Mary A. Everest, the wife of the author, under his oral instruction but without manual assistance. It speaks for itself regarding the results obtainable from the technic described, as do many fine mirrors made by the author.—Ed.)

Note the slight depressed ring at the center of this mirror which was later made into the perforated primary of a small Cass. The mirror was drilled from the back to within 1/16″ of the face with a copper cylinder, after the rough grinding had been completed. It was polished and figured in this condition, after which the plug was knocked out by tapping lightly on its face with a hammer. During the polishing this ring, 1/16″ thick, could not dissipate its heat as rapidly as the remainder of the surface. As a result, the ring was swollen out, polished off and, after coming to equilibrium, became a depressed zone.

and the depth of the curve. For shallow mirrors, which will include most amateur sizes of $f/8$ or thereabouts, the general appearance of the doughnut will tell the story. For the upper curve, the crest will appear too sharp, as in Figure 22, at the left, and for the lower curve, it will appear too flat. The correct appearance will be about as in the same figure, at the right. For mirrors of more pronounced curvature, where the depth of the shading makes it difficult to see the over-all correction at a single view, the shadow limit will spot the trouble. For the upper curve, the shadow limit will be

too near the crest; for the lower one, too far away. And if we have developed a sensitive touch in pressing on the side of the bench, the shadows for the upper curve will slow down too much at the crest; for the lower curve, they will jump across too fast. For still larger mirrors, which takes us up out of the amateur class, actual measurement for center of curvature of successive zones, in not over ten percent steps, is required to determine the figure with the necessary degree of accuracy.

A frequent error in amateur mirrors having the correct difference between inside and outside centers of curvature, is misplaced crest when the knife-edge is in the 50 percent position. The crest is too far in or too far out. These are shown by the dotted lines in Figure 23.

With the exception of the final test to prove the perfection of figure, the

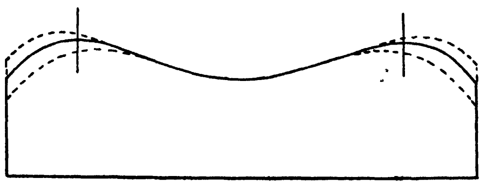


FIGURE 23

purpose of all testing is to determine the comparative thickness and radial location of the surplus material which is to be removed. In most cases this may be estimated at a glance, with the aid of the measuring stick. In other cases, after measuring up, it may be advisable to draw on a piece of paper the cross-section of the surface seen, superimposing this curve upon the curve of nearest fit from the doughnut family. Then the area between the two curves will represent the material to be removed.

For the upper curve in Figure 21, it can be seen at a glance that the greatest thickness of surplus material is at the crest, gradually tapering off into the adjoining zones. For the lower curve, however, it might be advisable to draw underneath a true 50 percent curve, such as the one shown in the doughnut family, but with the y values cut down to get a closer fit. Removing the material indicated would bring the surface to a true paraboloidal *shape,* but under-corrected, after which the crest could be brought up by regular parabolizing methods. A similar process is indicated for both cases in Figure 23, reducing the figures to the correct shape, but under-corrected. With a little experience, this process of superimposing the surface seen on the correct surface, will generally be a mental one.

For the medium deep curves, we can get along in similar fashion. But, for the big fellows, where all but the crest is so brightly illuminated or so deep in shade that the over-all figure cannot be seen under any conditions, complete zonal measurement in not over ten percent steps is required, after which some laborious graphical work based on these measurements is necessary in order to determine the exact condition of the figure.

From One TN to Another

As the reader has probably surmised by now, this paper is being written backward, so that it will line up with "A.T.M." *

Pitch: This, as far as the optical worker is concerned, is any material which will gradually yield or flow, and take on permanent deformation under pressure. If it fulfills these requirements, the main thing we are interested in is its "temper," which, for clarity, we may define as the number of seconds required to produce a quarter-inch dent in its surface with one pound pressure of the thumbnail. Thus we may speak of 5-second pitch, 20-second pitch, etc. The proper temper is secured by boiling to make harder, or melting and thoroughly stirring in turpentine to make softer, and then giving the thumbnail test on a sample teaspoonful which has been submerged in water at the working temperature for at least ten minutes. Optical workers use everything from the highly refined wood pitches of various trade names sold by the dealers, down to ordinary road tar. It is said that the mineral pitches have a much wider latitude in useful working temperature, and this is certainly desirable. *We* were brought up on common hardware store rosin and turpentine, probably the most cussed of the cussed, but we are still thriving on it, and are in no position to recommend a selection from the others.

Abrasives: Most tyros start out with the idea that grinding will result from the use of Carborundum, and polishing will result from the use of rouge. That's wrong. Both are excellent abrasives, and either may be made to grind or polish at will, depending upon how it is used. Two pieces of flat plate glass will soon become fine ground if rubbed together with rouge mixture between. On the other hand, a pitch tool, properly charged with finest Carborundum, will produce quite a respectable polish, compared with what might be expected. So here's the rule. Rolling abrasives grind, due to a chipping action on the brittle surfaces between which they roll. Stationary abrasives on one surface polish the other, the action this time being a fine scraping or smooth wearing away.

The spit test: This rough and ready procedure for keeping track of the radius of curvature during the roughing out, has stood the test of time. The routine is as follows: Provide a mirror rack in some corner of the cellar, to be used only for this purpose. Place the mirror in position and drop a plumb line from its face to the floor. Make a chalk mark on the floor at this point, measure back to where the desired center of curvature should be, and mark this point also on the floor. To test the mirror, wash off the grit and, while the surface is still wet, place the mirror on the rack, hold a lighted candle close to the side of the observing eye, find the image in the wet surface, walk back till the mirror fills with light, and drop a gob of spit. Compare this with the chalk mark and there's the answer. One TN's wife added a can of chloride of lime to the technic.

Non-evaporating liquids such as thin oil or glycerine are unnecessary for

* Let the reader judge whether the author's backward writing and arrangement are in a class with the triple-compound, ingrowing variety in "A.T.M." As a writer-backward he is only a beginner, a tyro.—*Ed.*

thus keeping track of the radius of curvature since, with a few trials, this method may be performed so quickly that the plain water film will last long enough for the purpose. When the correct radius of curvature has been about reached and more sensitivity is desired, bobbing the head will cause the characteristic knife-edge shadow to dart across the mirror. During the rough grinding, the water will generally form in vertical streaks on the mirror, making it difficult to see the shadow go crosswise. The head should therefor be bobbed *up and down,* causing the shadow to move vertically between the streaks, and making it easier to read.

After the first stage of fine grinding, the surface will be smooth enough to permit the actual figure on the mirror to be seen, the iris of the eye acting as a knife-edge. This effect, of course, will show up only when the eye is at a very critical point very near the exact center of curvature, making the test at this stage accurate to a fraction of an inch. Needless to say, the spit must be allowed to drop straight down, and not be ejected in a parabolic path.

Tool effect: This term refers to the more rapid grinding or polishing which always occurs in that zone of the mirror which is at the edge of the tool at the end of the stroke, provided the edge of the tool is in contact. The cause is obvious. At the end of a stroke, the unsupported area of the mirror partially counterbalances the opposite side, relieving the pressure there, so that the greatest pressure is at the edge of the tool nearest the unsupported area. The net effect is, to a minor degree, the same as with the overhang stroke made parallel to this edge of the tool, except blended out more into the adjacent zones. If the edge of the tool has been ground down excessively, or the edge of the pitch lap has been pushed down, the cause in either case having been long strokes or overhang, the tool effect will, with shorter strokes, be somewhat farther in where actual contact ends. A related effect is present when grinding or polishing face up with *circular* sub-diameter tools, unless there is a frequent change in the chord of the mirror over which the stroke is directed.

Thermal effect: This is distortion of the mirror's surface due to localized heat or cold, caused by the heat of polishing friction, or the temperature drop of evaporation from areas of the tool and mirror exposed during the stroke; and since glass has a coefficient of expansion running into significant figures, the hot spots will tend to swell out and the chilled areas shrink away. If the ball of the thumb is held against the face of the mirror for a moment, and the mirror is then placed on the testing stand, a pronounced thermal bump will be seen. In fact, with a little experience and our knowledge of the amount of magnification of the test, we may estimate approximately how many millionths of an inch the bump protrudes.

If polishing is resumed before the bump has receded, the first effect will be a more pronounced swelling of the bump, since it will receive more friction than the surrounding area. But, due to this additional friction, the bump will also be polishing faster up to the point where its excess heat is dissipated as fast as produced, when the bump will suddenly shrink back

and be replaced by a hole. This experiment may be readily performed with ordinary glass, and seems to explain the cause of the dog-biscuit surface such as shown in Figure 24. The protruding areas will behave in exactly the same manner as the thumb mark; after a little polishing they will recede and the valleys will become the bumps. This would indicate that the whole surface of a mirror is in a constant state of slow, irregular oscillation during polishing, if the polishing speed exceeds a certain limit. As a result, there is a definite limit to the speed with which fine optical work may be performed, this limit becoming a matter of instinct if the worker is alert to what is going on. The greater the polishing drag, the slower the stroke must be,

FIGURE 24

so that the result of the two will not exceed the allowable heat of friction per square inch. Here the hand worker has the advantage over those working with machines, since he can tell the amount of drag much better by the "feel" than he can by the groans of a machine. This is probably offset, though, by the fact that the machine worker is generally content to take several times as long to polish as by the hand method, since he doesn't have to work. Assuming that he keeps out of this dog-biscuit mess, as is quite likely if Pyrex is used, there are still two general thermal effects which must always be considered, since they are present in all polishing operations, and particularly with the usual amateur practice of polishing face down on a full-sized tool. One of them is also present during the grinding operation, if water is used as the abrasive vehicle. These will be given separate headings for easy reference later on.

Evaporation effect: The relative humidity of the average cellar with the furnace running is quite low, a difference of 10° F. between wet and dry thermometers being common. From the thermal coefficient of Pyrex, $.036 \times 10^{-4}$, we may calculate that a standard 10″ disk of this material will shrink over 30 millionths of an inch in thickness if kept wet and exposed all over long enough to assume a uniform temperature throughout. Under actual working conditions, when only the under side is wet, and only partly exposed part of the time, what really happens would defy analysis. But we may reason that the net effect would be a shrinkage, about as shown in the shaded portion of Figure 25, at the left; deepest near the edge where it might be five or six millionths, and tapering down to zero at the edge of the tool for the position shown. With plate glass the effect would be three

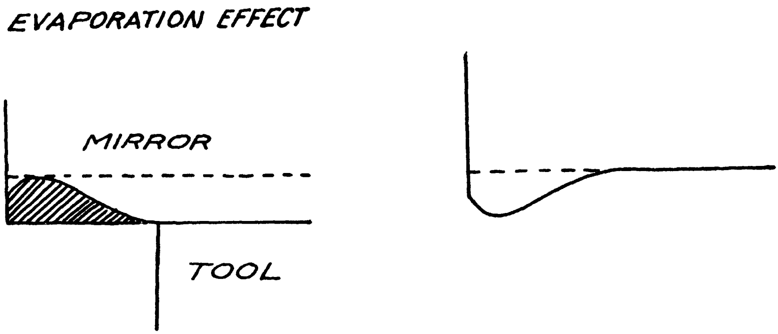


FIGURE 25

times this amount—certainly something to be considered. If the edge of the mirror is *dry*, the shrinkage will be held back one-half at the very edge, resulting in the little downward hook shown. Grinding the mirror in this distorted condition will bring it spherical for the moment, as shown by the dotted line. But when it comes to equilibrium, after removal from the tool, the zones affected by shrinkage will swell out again as shown in Figure 25, at the right, resulting in a final figure exactly the opposite of that caused by evaporation—oblate spheroid with *turned down edge.* With Pyrex, this is not a gross affair, but with ordinary glass it results in a grinding hangover with turned edge as deep as the final over-all correction. The remedy is obvious. Work in an atmosphere of high humidity, keep the mirror and equipment wrapped in wet packs while working with them, or use non-evaporating mixtures. For the amateur's purpose, kerosene is recommended for the final stages of grinding. As an interesting experiment, wrap a bit of kerosene-soaked cotton around a thermometer bulb and hold it in front of a fan, to get quick action. Nothing happens. Try the same thing with water and watch the temperature go down. Of course, kerosene cannot be used for polishing because of its softening effect on the materials of which

polishing laps are made. But here we shall find an offsetting factor, as far as the edge is concerned.

Friction effect: From our consideration of the tool effect, it is evident that the heat generated by polishing friction from one-third strokes will swell the surface about as shown in Figure 26, left, the effect at the edge being held back again due to the more rapid dissipation of heat at this point. The final result will be about as shown in Figure 26, right—oblate spheroid again, but this time with *turned up edge.* The over-all effect on the surface accounts for the reduction in the figure of a mirror which is cooling on the testing stand after polishing with normal one-third strokes. But, lest we fall into the error of accepting this as an infallible rule, let's consider another case—polishing off a central bump.

The first effect will be as in the thumb experiment above. The bump will

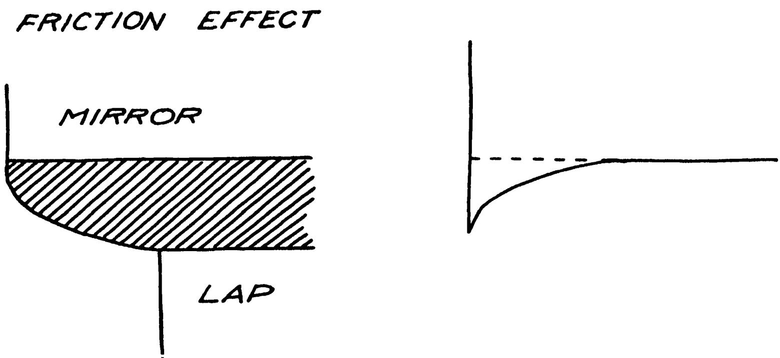


FIGURE 26

swell up, and even though we polished off much of its surface, we cannot see this immediately after its return to the testing stand. Assuming that nothing has happened, we may place it back on the lap and scrub a little harder at that central area. Perhaps, again, no results are seen. But after several such attempts, the bump will suddenly start to shrink back as we watch, winding up in a decided hole. Most amateurs do this at least once in their experience. And here we have a case where the figure of a cooling mirror changes in the direction of over-correction. In other cases, where the friction effect has been somewhere near an average of the two above conditions, very little change will be seen. The average worker doesn't realize the amount of heat generated. Almost all polishing work is dissipated in the form of heat, in contrast to grinding where most of the work performed goes into the actual removal of glass. The specific heat of glass is about .16, and assuming a polishing drag of 2 or 3 ounces per square inch—nothing unusual—and wading through the calculation of B.t.u's, calories, foot-pounds, etc., a 10° to 15° F. rise in temperature will be found to be a normal oc-

currence after a spell of polishing. This was actually checked by a thermocouple sealed in the bottom of a hole drilled nearly through a mirror. All of which means that, as far as the edge is concerned, the friction effect may, with luck, just offset the evaporation effect, so that the extreme edge stays clean-cut. And for those who are cranks on getting a diffraction edge, it is possible, with still greater pressure, actually to turn up the edge by means of this procedure, using a tool hard enough to stand it, in preparation for polishing out to a sharp cut-off in the final figuring operations. With ordinary glass, this would most certainly result in dog-biscuit, with the probability of damaging the edge again while getting rid of the dog biscuit. But more of this later.

Tool deformation: This was mentioned under "Tool effect," where long strokes or overhang caused excess action at the edge of the tool. During grinding, this need not be considered, as the one-third or shorter strokes used in the final stages will bring the mirror spherical within the limits of the material still to be removed. But in polishing with a normal pitch lap, the effect is also in evidence with the one-third stroke. The mirror passes over the center of the lap quickly, and comes to rest with the greatest weight at the edge of the lap for a comparatively long time, so that the edge of the lap is slightly ahead of the center in the process of slowly sinking down. The effect could hardly be *measured* in extreme cases, and with the one-third stroke it could not even be *seen,* judging from any difference in the appearance when examining the contact through the mirror. But we know from the behavior of the lap that the effect is there, at least in the form of reduced pressure from the marginal facets, so that the only time they are having full polishing action is at the end of the stroke. As a result, the center of the mirror polishes faster than the edge, and it takes several times longer to get a complete polish out to the edge than would be the case if the mirror were polishing evenly all over. This excessive center polishing would tend toward a hyperbolic figure if it were not offset by the evaporation, friction and tool effects, all of which work in the opposite direction, as we saw above. So, with the pitch tool, the mirror will generally come through the preliminary polishing stage very nearly spherical, and the amateur making his first small mirror might go right through the whole process without discovering that any of these effects existed, and believing that the slower polishing of the marginal zone was due to this zone being off the lap during part of the stroke. This is wrong, of course, as will be seen at once if a rigid lap is used, such as HCF cemented tight down to the glass. Using exactly the same stroke, the edge will polish as fast as the center, since HCF will not sag from the weight of the mirror, and its wearing action occurs only when the mirror is in motion. But now, without the pitch lap's tendency to deform, the various oblate spheroid tendencies mentioned above will cause the mirror to emerge from the preliminary polishing with this type of figure.

Tool plowing: This is a minor effect, but let's not skip anything—half the fun of the hobby is just thinking about it and trying to figure the "why" of everything, no matter how insignificant, as we stumble along. Assuming a

sinking speed of the facets of .010″ per hour, and 60 strokes per minute, the lap will be sinking three millionths of an inch *per stroke.* No sinking occurs at the edge while it is uncovered during half of the stroke, but when the mirror is slid back across this area, its edge will plow into this slightly higher pitch about the same as sliding the foot sidewise through mud. The result is a turned edge of perhaps one millionth of an inch in thickness, extending in about one quarter of an inch. We can see, from Figure 27, that the slope of such a turned edge would be about the same as the slope of the marginal zone of the 10″ doughnut, so that it would *appear* to be a gross affair. The answer to this one is a harder lap *or* reduced pressure.

The clock stroke: This is for those who, like the writer, get dizzy walking around the barrel, and for those who suffer the costive effects * of long hours in an office chair, the side strokes at three and nine o'clock will be found an efficient form of subdiaphragmatic * exercise. Mount the lap at the edge of a firm bench, at the proper height to bring the forearms in a horizontal position. Stand with the feet about 18″ apart. Imagine the lap

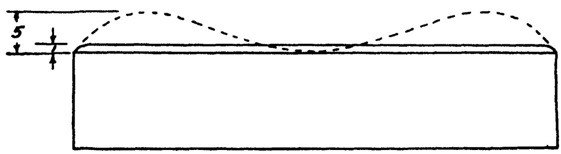


FIGURE 27

to be the face of a clock. Make the first stroke to 12 o'clock and back to 6, next to 1 and back to 7, then to 2 and over to 8, and so on around the dial. As the strokes are made, rotate the mirror very slowly in a counter-clockwise direction, making from 1/8 to not over 1/4 revolution of the mirror for each cycle of strokes. Rotating the mirror in the same direction as that in which the strokes progress might result in the same side of the mirror getting most of the polishing for a long succession of strokes, making the surface lop-sided and no longer a figure of revolution. While getting accustomed to the "feel" of this stroke, try placing a small piece of paper, wet to make it stick, near the edge of the mirror, and see how slowly but uniformly it can be made to go around. Never allow the mirror to be turning at the end of a stroke. Just a slight turning should take place *during* the stroke. In normal grinding and polishing the action should come from the stroke, and not from the rotation of the mirror. This will give the most zone-free and blended results of the various tool and temperature effects.

The blending overhang stroke: Except to remove a narrow raised zone, the overhanging stroke should always be performed as shown in Figure 28, at left, where the zigzag line shows the path of the center of the mirror around the lap. This blends the action from the edge of the lap over a rather wide

* The author's more accurate language had to be slightly modified, as that puritanical old killjoy, Aunt Sophrony, suffered a spasm.—*Ed.*

zone of the mirror, instead of producing a narrow depressed zone. The direction in which the strokes progress around the lap, and the rotation of the mirror, should be as shown, for the same reasons stated in the preceding paragraph. The effects of this stroke are particularly noticeable when working on a central bump. With the proper length of stroke, depending on the diameter of the bump, it may be removed with practically no hangover; but strokes parallel to the edge of the lap will result in a hole in the middle of the bump, leaving a crater which is still worse to remove.

The semi-stroke: Although the reasoning may appear a little far-fetched, this stroke may work to advantage in some of the final touching-up, where it is desirable absolutely to prevent tool deformation and keep the surface of the lap somewhat complementary to the surface of the mirror. It is per-

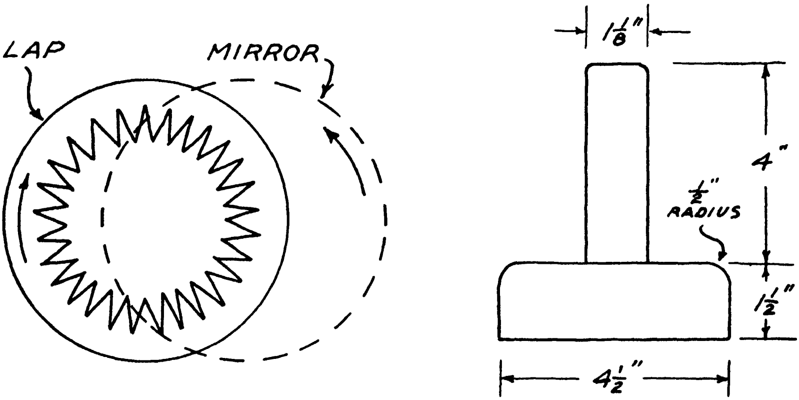


FIGURE 28

formed by sliding the mirror up to 12 o'clock and back to center, then to 1 and back, 2 and back, and so on around. This brings the mirror to rest at the center of the lap as much as at the edge, so that the central area sinks as fast as the rim, maintaining uniform pressure of all facets throughout the stroke. An alternative that is not so tedious, perhaps, is tapered pressing at the completion of each cycle of full strokes, starting with about 20 pounds additional pressure from the hands of the operator, and tapering down to zero pressure at the end of about 15 seconds, when the strokes are resumed.

Except for rough grinding and zonal correction with small polishers, the above three strokes, of various lengths as the occasion demands, will meet the requirements of amateur mirrors.

BACKWOODS TECHNIC

The handle: Use a hardwood handle, turned with vertical grain and a flange just large enough to permit a comfortable grip with the finger tips

and the balls of the thumbs. The dimensions in Figure 28, at right, are good. Cement the handle with about 30 second pitch, which is hard enough to prevent it from sliding around while in use, yet soft enough to prevent transferring to the mirror any warpage of the wood which may occur. Make certain that the handle is exactly central on the back of the mirror. Use a scale while the pitch is still warm, sliding the handle as necessary. Check this measurement at the beginning of each "spell." If found slightly out of position, loop a stout cord around the flange, as low as possible, tie the cord over to a post at the same height as the mirror and hang on it a weight to exert a steady pull on the handle in the direction wanted. A few minutes of this will do the trick, unless the mirror has been left over night on the testing stand, in which case it may take half an hour. If re-cementing is necessary during the last fine grinding or the polishing stages, do no work until the heat from the pitch has left the mirror.

The grip: Do not grip the central shaft. This is only for holding the mirror when it is off the tool, and for "sort of" guiding the hands to a uniform grip on the flange. The grip should be low down, with the finger tips

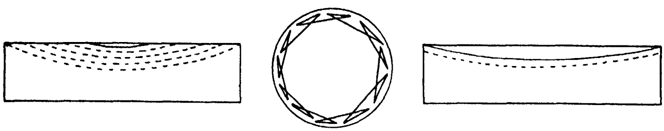


FIGURE 29

not quite touching the mirror. A high grip will aggravate tool plowing and turn the edge. During grinding, additional pressure may be applied by pushing the palms down on the glass, since thermal effects need no consideration here. But, during polishing, any pressure required should be applied to the top of the flange, and at the first signs of heat in the handle, this should be stopped. Whenever the mirror is being handled while off the tool, hold the free hand under it as if expecting it to drop off the handle. Just a little free insurance.

Rough grinding: Hollow out as shown by the solid curve in Figure 29, at right, not as shown by the dotted line. The latter means useless work, as well as wasting valuable thickness of the glass. For the first spell, use an overhang as far out as possible without tipping the mirror off the edge of the tool. The strokes are shown in Figure 29, center. Continue this until the spit test shows a central depression having ¼ to ⅓ the diameter of the mirror and the desired radius of curvature. If properly done, there will be just a few scattered pits outside this area. As soon as the spit test shows that the desired curvature has been reached, make the strokes over chords of the tool slightly farther in for a spell and spit test again. If the curvature is still right, keep going a little farther in with the stroke, the aim being to extend the concavity, as shown in Figure 29, left. At the time the full concave is reached, the strokes should have just come in to the

diameter of the tool, and the grinding should have just reached the center of the tool, about ⅓ strokes having been maintained throughout.

Use all the pressure desired in the rough grinding. The more pressure, the quicker the results. Add fresh abrasive as often as necessary to maintain a loud grinding sound. This will be rather frequent, at the start, as the mirror will push the grains off the edge of the tool nearly as fast as applied. But as soon as the concavity is well started, the abrasive will come to reason; and, of course, whatever is pushed over the side may be reclaimed. Just scrape it up, drop it in a glass of water, stir thoroughly and immediately pour off the gunk. The useful grains will be left in the bottom. If at any time the curve gets too deep, as indicated by the spit test, use strokes over chords a little nearer the center of the tool; if too shallow, stay a little farther out. Frequent spit testing while wiping the sweat off the brow, will indicate what to do.

If a tool is available which already has the desired radius of curvature,

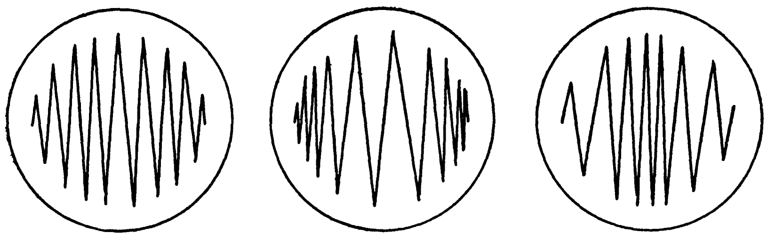


FIGURE 30

so much the better. Use it. In this case, forget what is happening to the mirror while working, and try to wear the tool uniformly all over, starting with the strokes shown in Figure 30, left. As the concavity in the mirror spreads, shorten the strokes a little, and as it approaches the edge of the mirror, gradually blend into the regular ⅓ straight diametrical stroke. Spit test often, as before. If the curve becomes a little shallow, work a little more to the outside of the tool, as shown in Figure 30, center; if too deep as in Figure 30, right.

Of course, none of these corrective measures apply to a curve which is found too deep *after it has reached the edge.* With any care, this will not happen. But if it does, it means reversing the tool and mirror. Both of the above methods of rough grinding are easiest performed on the barrel, and either may be depended upon to bring the mirror through very nearly spherical. But test, in order to make sure. If not experienced enough to see the figure as explained under "The spit test," the bubble test will tell close enough. Grind down the last wet a little, add some water, and then watch the bubbles as a long stroke is used to bring them out to the edge of the mirror. If they remain unchanged in size, the mirror is near enough to spherical for this stage. Watch at the edge in particular. If the bubbles be-

come smaller as they pass out under the edge, the edge is turned. If the mirror is not spherical, continue with the coarse abrasive until it is, using $\frac{1}{3}$ or slightly shorter diametrical strokes. The worst form of turned edge and slow edge polishing is a hang-over from this stage.

Fine grinding: For the fastest action, the fine grinding stages should be used only for the purpose for which they are suited—removing the pits of the previous stage. If the fine grinding stages are deliberately used to deepen the curve, this not only is a very slow process, but it takes several times longer than necessary to get sufficient grinding at the edge of the mirror, since most of it is occurring at the center. Here the professional, with his channeled cast iron tools which hold their shape and spread the abrasive in a uniform manner, has a decided advantage over the amateur with his glass tool which changes shape as easily as the mirror, and which cannot safely be channeled due to the liability of chipping and scratching the mirror. Two methods are open to the amateur for getting as fast grinding at the edge as at the center—shortening down the stroke to an inch or less, or using the regular $\frac{1}{3}$ stroke and reversing tool and mirror in the middle of each stage. For example, with ten wets per stage, grind for five wets with the mirror on top and then reverse for the other five. Leave in this position for the first five wets of the next stage, and then reverse again. And so on with each successive grade of abrasive. This method is a little mussy and requires some special equipment, and so, although it is a sure-fire method of finishing up with a spherical surface, we shall probably choose to stay on top. Even the recommended short strokes will shorten the radius of curvature a slight amount, and an inch or so should be left for this purpose after the rough grinding is completed. From a practical point of view, however, the edge may be considered to be grinding as fast as the center, and the grinding time per stage may be cut in half if the speed of the strokes is increased to offset shortening them down.

As soon as the noise of grinding dies down, add fresh material, first washing out the "mud" if any appreciable amount of this is present. Mud forms a support for the coarser grains of abrasive, slowing down their action to a marked extent. To wash out the mud, slide off the mirror, throw on a tablespoonful of water, replace the mirror and make the regular strokes to squeeze it out. One wet of this is sufficient.

For the last two or three grades of abrasive, use kerosene for the mixture, for the reason explained under "Evaporation effect." Also, during these later stages, be careful when adding fresh abrasive. Add the required amount to the center of the tool, plus three drops about 120° apart near the rim, for "balancers," lower the mirror carefully and parallel to the tool, so that when it touches the abrasive mixture this will be spread out evenly in all directions. Work the mirror very slowly, and actually hold up on the handle a bit so that it will take 10 or 15 seconds before the abrasive takes hold. Listen for the first sound of the coarser grains and let these take their time crushing down until the sound indicates a uniform grinding all over. Then take a few seconds more in gradually applying whatever pressure

is to be used. A little care like this will greatly reduce the liability of scratches, which generally occur when the mirror is first placed on the tool. Even an extra large grain will crush up without more than a pit or two, if the pressure is gradually applied as above. Of course, if the sound indicates a chunk of concrete between the surfaces, the mirror should be *lifted* off at once, and both surfaces flushed. And it adds a feeling of security, even with the sealed commercial grades, to settle them first in the water or kerosene, and use only the upper two-thirds.

With regard to pressure, it is safest to taper off to practically zero for the last grade. If the mirror has a weak diameter, any appreciable pressure here will result in an astigmatic surface.

The lap: If the addition of turpentine is necessary, stir thoroughly, and then stir some more. An egg beater is good. Variation in the temper among the tool facets, resulting from insufficient mixing of the pitch and

FIGURE 31

turpentine, will cause some of them to resist the pressure of the mirror more than others, and the action of such a tool cannot be depended upon. The stirring should be done just below the boiling point, so that the bubbles caused by stirring will rise to the surface after the stirring is completed. Bubbles do no harm after the lap is pressed, or while it is in use. But during use, when the pitch is under pressure and seeking an escape, the air in the bubbles is compressed; and during an over-night period of rest, the bubbles will swell out again, warping the surface of the facets. This makes longer cold-pressing necessary before polishing may be resumed. If well-stirred and bubble-free pitch is used, the lap will hold its shape for many days, and require only a few moments' cold-pressing at the end of that period.

In cutting the channels, a carpenter's rip saw with plenty of soap suds is a fast worker, after which they may be easily widened into the usual "V" section with a sharp knife. A rubber grid, made as shown in Figure 31, will save some time and eliminate most of those chips which fly around the place. Heat the tool to about 30° F. above working temperature, pour and

form the pitch in the regular manner to about the thickness of the mat, lay on the mat with the central facet properly located, and push it down into the pitch with the mirror and plenty of warm soapsuds until all but the marginal facets come up into contact. If the lap chills before the mat gets down to sufficient depth, remove the mirror and reheat the lap in a pan of warm water. After the proper depth has been reached, chill the lap under the cold water tap, remove the mat by pulling up at a corner, rinse off all traces of soap, dry the surface with an old piece of linen, paint hot pitch on the marginal facets to bring them up to the level of the rest, and then repress for complete contact all over.

The sinking speed of the lap deserves a little thought. This refers to the speed with which the facets reduce in thickness from the pressure of polishing. The lowest possible sinking speed will insure freedom from edge troubles. This involves pitch temper, heat of polishing and the resulting softening of the pitch, pressure used, diameter and thickness of the facets. Pitch hardness is limited to the point where sleeks are likely to result. With fine optical rouge, 20 sec. pitch for plate glass and 40 sec. for Pyrex seem to be about the maximum safe limits. With care in washing the rouge and applying it to the lap, these limits may be exceeded by experienced workers. But, for safety with super-hard laps, it is good insurance to paint on the thinnest possible lamination of about 10 sec. pitch, not over a few thousandths of an inch in thickness. Or scrubbing the surface with turpentine, and letting it air-dry, will generally soften the surface enough to remedy a lap which has a tendency to sleek.

The heat of polishing was mentioned a few pages back. A lap of 5 to 10 sec. pitch will behave fairly well for the first 10 or 15 minutes. But after the heat gets well down into the pitch, it will soften enough to cause tool plowing and a rapid closing in of the channels. Use of the maximum safe hardness of the pitch, as suggested above, will generally prevent the trouble. If it doesn't, the pressure should be relieved, and the proper polishing drag secured by correct adjustment of the rouge mixture. To determine this, start with a mixture having the consistency of thick cream. With this the rouge granules will act like so many ball bearings, allowing the mirror to slide easily over the lap and making the facets invisible through the mirror. This, of course is not a true polishing action. Gradually add water, a few drops at a time to exposed areas of the lap, noting how the drag gradually increases as the outlines of the facets begin to appear. Continue until the facets are just plainly visible, with an even red cast, and the lap has a heavy but *smooth* drag. With further additions of water, the facets will rapidly become dark and the mirror start to grab from glass-to-pitch friction. The best point is where the facets have the clear red cast, or just before, and the rouge mixture should be adjusted to produce this effect.

No set ratio of rouge to water can be given, as this varies with the grade of rouge and temper of the pitch. The size of the facets is limited from about 1″ for 6″ and 8″ mirrors, to about 1½″ for 10″ or 12″ mirrors. Larger facets have a tendency to produce zones. Regardless of where the

center facet is placed, there is never a uniform distribution of facets in all directions from the center of the lap. With too large facets there will be insufficient overlapping of the facet action to prevent zones. The danger is increased by the fact that the pressure of a facet is greatest at the center, tapering to zero at the edge where there is free escape for the pitch. This may be demonstrated by polishing for a few moments without rotating the mirror, keeping the strokes parallel to one set of channels. The surface, when tested, will appear as in Figure 32 at the left, not as shown at the right, same figure. For sufficient overlapping of the facets, experience dictates at least six or seven rows of facets across the lap. This will permit one-third or longer, straight, diametrical strokes without zonal difficulties. For shorter strokes, the necessary blending of the facet action may be obtained by mixing in side, circular and elliptical strokes.

In the matter of facet thickness, 3/16″ is a good starting point, trimming the channels as necessary until the pitch has settled to 3/32″. At this point the sinking speed will be only one-half what it was at the start, but the diminishing depth of the channels will make it increasingly difficult to squeeze

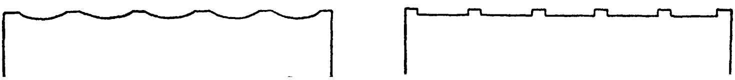


FIGURE 32

out the surplus rouge mixture after each application, and get the mirror in proper contact with the lap.

The edge facets also need consideration. With the regular method of channeling, these are all undersized, and since sinking speed is a function of facet diameter, these marginal facets will have less resistance to pressure than the complete facets farther in, resulting in turned-up edge. Trimming the lap or rounding the edges of the marginal facets will only make matters worse and these dodges should never be used in the preliminary polishing, when the aim should be in the other direction. A soft metal strap or plaster of paris dam around the edge of the lap will limit the flow, but these are hard to keep in adjustment just below the level of the pitch as it sinks. Another dodge is to dry up the lap and paint airplane dope around the edges of the marginal facets, allowing it to set hard before using the lap. Perhaps the simplest is to fill in the channels between the marginal facets with pitch, since this will reduce their sinking speed by limiting the flow to two directions, and also help retain the rouge mixture.

Polishing: Fine optical practice demands slow intermittent work, with temperature and humidity under strict control, using 50 hours or more to polish a 10″ mirror, and an equal length of time to figure. But who has the patience, or the necessary control of temperature and humidity to reap the benefits of such slow work? For the amateur's purpose it is just as well to polish as quickly as possible by any method that will preserve a figure of revolution, giving no serious attention to the figure until the polishing is

completed. The mirror will, of course, emerge from this stage looking under test like almost anything but an optical surface. But with a little experience in zonal correction this can be rapidly changed to a spherical surface with practically no evidence of zonal hang-overs, and these disappear in the final figuring. This preliminary correcting not only adds to the fun, but it tunes up mind and muscle so that in the last touching up of the paraboloid, the worker, and not the mirror, is the boss of the situation.

The main thing to watch for is astigmatism, testing for this at frequent intervals early in the polishing. If signs of this are found, work without pressure; if not, give 'er the works. The reasons for the hard lap have been given, and the strokes should be short enough to keep the marginal zone polishing somewhere nearly as fast as the center. The HCF lap, described in "A.T.M.," provides almost a fool-proof method of bringing the mirror through this stage with a brilliant, scratchless and sleek-free *visual* polish. But, since the pitch lap will be needed for the final work, many will prefer to go it on pitch from the beginning.

And here one must be ever on the alert to prevent scratches, taking a lesson from the busy spectacle maker who works with grit all over the place but seldom scratches a lens. He is just habitually grit conscious and keeps out of it. So roll up the sleeves, scrub up everything that is to be touched, including the testing equipment and under the fingernails, and never touch anything else. Carbo germs are dead ones and won't hop up on the lap of their own accord. When picking up the rouge jar, bring it around the lap, not over it. Etc. Frequent exchange of newspapers on the bench is good insurance, placing anything to be handled on clean sheets of white paper. Keep an eye on the visitors. These are always leaning on first one thing and then another, and just can't be made to understand.

Most scratches occur immediately after placing the mirror on the lap. So be careful in applying rouge. Stir thoroughly each time it is used, wait about five seconds and then draw from the top with a large medicine dropper. Run a narrow line of rouge along the center of each row of facets, and set the mirror down carefully to spread it out. Use ten seconds' tapered pressure, make a couple of small circular strokes to distribute the rouge better, and then press ten seconds again before starting to polish. Not only will this push any coarse grains down level with the rest, but all rouge granules will have a chance of getting a toe-hold in the pitch rather than being pushed off into the channels.

For uniform action, the direction of the stroke must be changed often. This can easily be seen the first time a pitch tool is used, before the surface gets too discolored. Apply thin rouge so that the facets can be plainly seen, and keep the strokes in one direction. The facets will take the rouge charge in streaks in the same direction as the strokes. These streaks will throw minute thermal bumps on the mirror, resulting in a "lemon peel" surface. Change the direction of the strokes 90° and the first streaks will gradually be replaced by others in the new direction. Now go into the clock stroke and the facets will soon take on an even hue all over. Lemon peel is too

insignificant to worry about during polishing, but this was a good time to mention it, with a fresh lap to demonstrate the cause.

Correcting: The best way of keeping track of things from now on will be to think at all times in terms of what is seen on the testing stand; imagining any irregularities in surface contour to exist actually as they appear, even while the mirror is on the lap. Instead of millionths of an inch, this will mean seeing and removing material *eighths* of an inch in thickness; even getting a thrill, perhaps, from rubbing off this much with a magic touch of the finger-tips around the rim of the mirror. Early in the work it will be essential to form some rather definite notions regarding how fast a certain polishing drag and speed of stroke will remove one of these eighths, or perhaps only a sixty-fourth of an inch, especially where local polishers are used, with the action concentrated in one zone. To complete the illusion, the magnification of the test may also be applied to the sinking speed of the pitch, softening it down so that instead of, say, .002″ per hour, the facets are pushing down at the rate of .05″ per second. Consideration of what happens when our imaginary

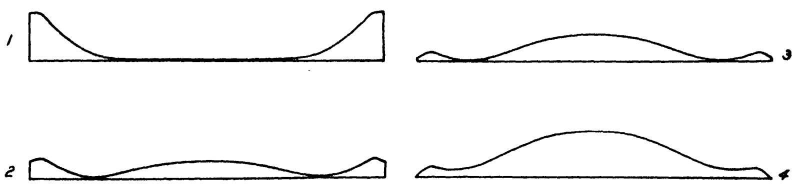


FIGURE 33

mirror is moved over such a lap with various degrees of pressure, and different speeds and lengths of strokes, will show at once the cause of certain peculiarities of lap behavior which otherwise would be hard to understand. And in case there are any misgivings as to when we shall hit bottom, there is a quarter mile to go!

Correction involves the proper setting of the knife-edge, comparing the surface seen with an imaginary sphere tangent to its lowest zone, and polishing off the glass located between the two.

If an accurate, predetermined focal length is required, the knife-edge must be set at the center of curvature desired for the marginal zone, the mirror leveled off from this position regardless of the work involved, and then deepened into the paraboloid. Thank goodness, we amateurs have no need for this. We merely choose a knife-edge setting that will represent the least amount of work. This does not necessarily mean the removal of the least amount of material, since it is always easier to work on the central and intermediate zones than near the edge. We can well afford to push the knife-edge slightly toward the mirror, causing the center to bulge out to quite a considerable extent, if this will reduce the amount of work near the edge. Figure 33 shows, in somewhat exaggerated form, apparent cross-sections of the surface usually found after fast, short-stroke polishing on a hard lap,

with no regard to figure—oblate spheroid with turned edge. Turned edge goes with this figure and the cause is easily visualized as we picture the edge being dragged over a lap which has gone spherical after a few seconds of polishing. A wet tape around the mirror would have prevented the evaporation edge hook, while judicious scraping of the HCF, or pressing down of pitch facets, would have counteracted the oblate spheroid tendencies. But we were in the usual hurry and didn't do this. The second curve looks like the least amount of material above the sphere, but the third one is the easiest to correct. Here the depth at the edge is practically the same as that of the low zone farther in, giving the least amount of edge correction for any of the four curves. Regardless of the general figure, it is almost an invariable rule, when turned edge is present, to select a knife-edge setting where the extreme edge appears of the same depth as, or very slightly higher than, the lowest zone within. (See the illustration in "A.T.M.," in the chapter "The HCF Lap.")

In estimating the thickness and radial location of glass to be polished off, the eye alone is sufficient until the surface is reduced to the extent that sensitive adjustment of the shadows is necessary to show any zones. For that third curve, for example, there is no use whatever of attempting to form an accurate estimate of the exact shape of the central bump, and then trying to juggle lap and stroke to remove that exact amount of material. Too many things would happen before the job was completed. And so, for the first trial, it is just as well to take rough cuts to get down to an approximate sphere, the only precaution being to see that we don't go too deep. But after the surface is planed down to the extent that only slight zonal hang-overs remain, it is well to put on the measuring stick for accurate radial location of the high zones, estimate their thickness as near as possible, and then attempt to make the lap or local polishers behave accordingly.

The methods available to bring the preponderance of polishing where it is wanted include local polishers, deformed lap, and special strokes. As a rule, local polishers for edge work, deformed lap for intermediate zones, and overhang for central protuberances will give the fastest and safest results without producing undesirable effects in other parts of the surface. But this will depend also upon whether the surplus to be removed is concentrated in one narrow zone, or is spread out and well blended into adjacent ones. Also, for the first work it is OK to adapt the fastest method possible to get down somewhere near a sphere, although this would be intolerable later on due to the thermal effects produced.

As might be expected, the writer recommends the HCF method where local polishers are indicated, especially for the preliminary rough work. Certainly no other method is faster, or more effective in concentrating the action where wanted. But it must also be said that no other could cause so much trouble if carelessly used. A rigid plaster of paris and HCF tool should be provided, to hold the strips, as described in "A.T.M." They would soon wreck a pitch lap beyond any possibility of bringing it back to contact. Strips of various widths, straight ones, arc shapes of various radii, and

irregular pieces should be kept floating in a pan of soapy water, ready for use. The soap will make the rouge stick. For the rough work the rouge may be mixed as thick as possible yet still permit the points of the HCF to be seen through the mirror. But, for light touching up, later on, the mixture should be thinned down and the pressure relieved to produce a smoother action.

For small pitch polishers, the glass feet used under furniture legs make excellent tools, giving a good grip for the fingers. They should be ground to approximate curvature against the mirror while it is still in the rough grinding stage, and of course, no further grinding is necessary. These polishers must be used with the mirror face up, with a fine grade of rouge to prevent sleeks, and they require frequent renewal of the rouge mixture.

Deforming the lap to concentrate its action in certain zones, or remove its action in others, is standard practice with many amateurs. This includes pressing down the marginal facets with the mirror, and pressing or raising facets farther in. Only a slight amount of pressing is required—just enough to cause the facets to take on a slightly cloudy appearance from the greater thickness of rouge mixture between them and the mirror, and to eliminate their action for perhaps five minutes while the rest of the facets are sinking to the same level. In pressing the marginal facets, plenty of pressure should be used while the mirror is slowly pushed around the margin of the lap, the idea being to accomplish the pressing without much polishing. For pressing down facets farther in, lay on squares of paraffined paper and press with the mirror. To raise them up, lay on squares of HCF and press with the mirror; this time, the pitch, seeking the easiest means of escape, will flow up into the HCF depressions. Go easy with this one.

Whenever edge correction is necessary, it is advisable to do this first, so that the slight irregularities left by the local work here will be removed by later work on the full sized lap. The HCF method described in "A.T.M." is our choice for this, leveling out as close to the edge as possible, and then removing the last quarter-inch raised zone with the finger tips. To do this, place the mirror face up, with the handle down in a milk bottle, paint rouge around the marginal zone, and make about 1" strokes parallel with the edge of the mirror. Use the tips of the first three fingers just inside of, and extending to the edge; using the thumb as a guide against the side of the mirror. Use plenty of pressure and revolve the mirror slowly by grasping the flange of the handle with the other hand, so that each stroke advances about one-quarter inch past the previous one. Three revolutions of the mirror is enough of this without testing to be sure the action is where it is wanted and not producing a ditch.

In wiping up the mirror use two pieces of cheesecloth kept hanging, when not in use, on clean hooks overhead. Use one to sop up the surplus moisture, fan dry, and wipe lightly with the other to clean off the dried rouge.

When removing a central protuberance, the first consideration is to protect the edge. Until the bump is polished down to the proper level, the edge will quickly turn if allowed to drag over the lap. Irregular shaped

pieces of HCF of such a size that the stroke will just bring them to the boundary of the bump will quickly take the preliminary rough cut and, of course, cannot possibly harm the edge. To make the mirror properly balance, three small pieces of *clean* HCF may be placed around the margin of the tool, with soapy water applied to make the mirror slide easily over them. If the first attempt starts a hole in the middle of the bump, leaving a crater, never mind. Go ahead until the hole appears to be down nearly level with the marginal zone and then remove the crater with an HCF ring, still using the balancers. In all this work the strokes should be extremely short. When the leveling off has proceeded to the point of slight zonal hangovers in the form of raised rings, these should be located with the measuring stick, and the stick used to locate the strips on the tool. At this point several zones may be worked on at the same time by placing strips as indicated for each, giving a larger area of support for the mirror and softening down the action.

In using the blending overhang stroke, to remove a central bump, the marginal facets should be well pressed down, using an overhang well out to the edge of the lap. As soon as this is done the overhang should be pulled in a bit to prevent forming a hole. If a hole should start, remove the crater around it at once with a *spinning* overhang, rotating the mirror rapidly with the palms of the two hands against the side of the handle flange, keeping the crest of the crater just inside the rim of the lap and gradually working the mirror to new positions to equalize the facet action. What happens here is easily visualized. The action tapers off to zero at the center of the mirror, in spite of the fact that the center is in complete contact.

In all overhang polishing, after the mirror has been brought spherical, press often. About half a minute polishing, and 15 seconds tapered pressing with the mirror centralized, is a good rule to follow here. If the lap is allowed to become of shorter radius of curvature than the mirror, it will produce a hole in the center of the mirror, regardless of the stroke used. Keep the edge of the lap hitting, and learn just what happens with the various strokes under this condition.

In bringing to spherical shape by the overhang method on the full sized lap, zonal hangovers will generally be broad ones blending well into each other, which may be rapidly reduced by pressing in a few facets in some zones, and raising those in others, as the case requires.

After a few optical surfaces have been made, the amateur learns from past experience how to apply the necessary preventive measures to bring the mirror through spherical and to eliminate most of the correction mentioned above. But it does no harm to get into all this mess at least once, so that the tricks will be learned and held up the sleeve to deal with one of those mirrors that just won't behave.

Assuming that we have gone as far as we dare with the local stuff, there will remain some blending and refining of surface texture to produce an *optical* surface. For the proper humidity to reduce evaporation effects, it

is well to sprinkle the cellar floor thoroughly several hours before this is started, and keep it wet thereafter. In the absence of wet and dry bulb thermometers, the presence of large drops of water on cold water pipes will indicate a good condition. It will also be advisable to keep the wet tape around the edge of the mirror, extending down as close to the lap as possible without actually hitting it. This must be removed when testing, of course, and be kept scrupulously clean. Glycerine mixtures will further hold back evaporation, but plenty of soap in the water—enough to cause a layer of fine bubbles on the exposed areas of mirror and lap—works just as well. It is probably the dead air spaces in the bubbles that do the trick, insulating the surfaces for the fraction of a second they are exposed. Next we must watch for oblate spheroid tendencies, since short strokes will be needed to keep full action out to the rim of the mirror. Keeping the facets pressed down wherever the low zone has a tendency to form will accomplish this, starting with two or three and pressing more later if the test so indicates. But don't press them so that it will require more than a few minutes to bring them back to contact, just in case the test shows the wrong ones to have been pressed to get the correct action with whatever stroke is being used. Paraffined paper is cheap and it is better to press often than too much.

The object of this spell is to clean up those hangovers and polish out to a sharp cut-off at the edge. The latter will be shown by the diffraction line that develops during this stage—just a faint spider web of light around the left edge of the mirror at first, but becoming brighter and brighter until both sides have about the same illumination. The main thought here is to gradually taper off the pressure and speed of strokes as the surface cleans up, with frequent change in the variety of strokes, small circles, ellipses, etc., in order to prevent any possibility of throwing up facet zones. And use plenty of pressing, of course—the main reason this time being to equalize any heat present. For those who have been brought up to fear elliptical strokes, we must add that, after the mirror has been once leveled off and is prevented from developing an oblate spheroidal figure, no type of stroke will turn the edge if the recommended hard lap is used. Of course, were we to start a central depression, and then spread this out to within, say, a half inch of the edge, that half inch might now be called turned edge. But we can hardly say we have *turned the edge* when we haven't even touched it.

Figuring: Here again there is considerable latitude in the methods which may be used. Perhaps the most fool-proof is face up with a half-sized star lap, using the strokes shown in Figure 30, left, so that the points of the star just pass over the rim of the mirror. This may be done on the milk bottle, gradually revolving the mirror with the free hand. Every attempt should be made to preserve the paraboloidal *shape* throughout, gradually increasing its intensity until the desired depth has been reached. This should be checked as soon as there are any signs of a figure, measuring the difference between the inside and outside centers of curvature, setting the knife-edge half way between the two, and then checking the crest for the 70 percent position. If the crest is too far in, shift to the strokes shown in Figure 30, center;

if too far out use those shown in Figure 30, right. Try to determine the proper strokes early in the figuring and hold to them.

The distribution of material to be removed can be seen by laying a straightedge across the top of the last curve in "The Doughnut Family." It is also important to preserve the flatness of the central area when the knife-edge is at its center of curvature, and not develop a hole. The first curve in the family shows the proper cross-section. As the difference between inside and outside radii of curvature approaches r^2/R, work should be more and more leisurely, with plenty of time on the testing stand for the mirror to come to equilibrium. For the final test, the mirror should be left several hours; for Pyrex, one hour will do. For deep curves in the larger sizes, this sub-diameter lap method is recommended, but be careful of scratches. For the deepest ones, the facets may be backed with some yielding material such as felt or rubber between glass and pitch, to allow good contact at all parts of the curve. This will make some readers gasp, but it works, and has been used often without throwing the surface out of revolution.

For the smaller mirrors, and up to 12″ with aperature ratios of $f/8$ or so, fine figuring may be done face down on the full sized lap. Long strokes may be used, starting with about ⅞ length and working back to ¾ or ⅝. Watch as above for the position of the crest, as soon as it can be seen. If too far in, shorten the strokes, if too far out, lengthen them. Absolute contact must be preserved with long stroke parabolizing. Otherwise the deformed lap will put a hole in the middle of the mirror. Fifteen seconds of work, and fifteen seconds of pressing is the rule. The worker must feel that he is pushing material away from the center of the mirror with the edge of the lap. If unexpected high zones develop, they may be treated with the blending overhang. In fact, the final stages of figuring will generally develop into a mixture of long strokes and then overhang, alternated in order to keep the curve smooth. Practiced hands will also include long elliptical strokes, but these require considerable experience, as the pressure must be tapered *during the stroke* to prevent the formation of undesirable zones.

Take plenty of time in figuring. Let it be mostly thinking. Both are good for mirrors. With plenty of testing and thinking, and preventing backtracking by taking the proper corrective measures the moment their necessity arises, the actual labor involved will become almost insignificant.

The Second Mirror

Well, as we read over what we have written, we cannot help but chuckle. While we hope all this will help the beginner to sense his problem, we can hear the question, "Does all this go with making a mirror?" To which the answer is NO! For those who have been through the experience once, and understand what is going on during the various stages of the work, our recommendations would be as follows.

Use Pyrex and forget thermal effects.

Rough grind as recommended, being sure to bring spherical before going to the finer grit.

Fine grind by the reversal method (our dingbat shown in Figure 34) bringing through strongly overcorrected—about ½" greater than r^2/R. This will just show in the spit test, and will give just enough material to battle the oblate spheroid tendencies of fast preliminary polishing on a hard lap. To produce this curve, start with about one-quarter strokes for the first stage of fining. Grind down a wet once in a while and, if there is any tendency to grab when the mirror is at the middle of a stroke, lengthen the stroke slightly for the next wet and try again. As soon as the minimum stroke possible is found where no grabbing will occur, use it for the remainder of the wets of that grade. With successive grades it will be necessary to lengthen the strokes very slightly. For the last three stages lengthen the

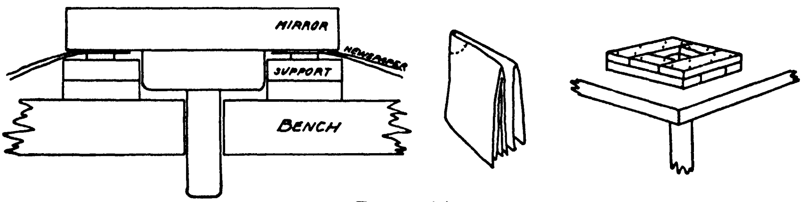


FIGURE 34

strokes just enough to show a faint hyperbolic figure in the spit test. This will be very nearly one-half strokes.

The kerosene will be of no advantage from a thermal standpoint when Pyrex is used, but it will do away with those central air bubbles which are bump producers.

From now on it is clear sailing. Don't bother to bring spherical but aim for the paroboloid from the beginning of polishing. Get on a 40-second lap and, as soon as it is possible to test, locate the crest with the knife-edge in the half-way position. Start with a stroke which will bring the edge of the lap not quite to this crest and give 'er a spell. On wiping up, the marginal zone will be found to be polishing fast, with the center scarcely touched. Fine. Under test, the diffraction edge will have already put in its appearance and will be a guide from now on.

As the hyperboloid approaches a paraboloid, the point will be found where the left diffraction edge begins to lose its brilliance, with a softening of the illumination just inside—warning that turned edge is approaching. This is the signal to lengthen the strokes just enough to bring the diffraction line back again. The cause of edge turning here is obvious. With short strokes, the edge of the *lap* turns up, and as the mirror approaches a sphere its edge will plow into this high pitch.

This lengthening of the stroke will slow down the speed with which the correction reduces. But remember that, with the hard lap, the strokes must be much longer to produce a sphere, and to hold a paraboloid they must be lengthened to about three quarters the diameter of the mirror. As a result, the correction will keep reducing with one-half or even five-eighths strokes,

whatever is necessary to hold the diffraction line at the edge or to bring up the center polish.

Well, that's all there is to the writer's method of making a mirror. As soon as the figure reduces to the paraboloid, the stroke is lengthened in order to hold it there until the polishing is completed. We are so familiar with the method that we once got a little cocky and made a wager that we could produce a mirror by "feel" alone during the grinding, and "appearance" of the polish as it came up; getting a correction within 25 percent over or under without testing at all. After the job was done we pulled in our horns and bought the cigars without argument, as the mirror was only half corrected. But, anyhow, it took only ten minutes to finish.

In Retrospect

And now, as we sit back in relaxation after the arduous task of writing all we know about mirrors, and perhaps a little bit more, we must pay tribute to the numerous amateur mirror makers whose correspondence has been a constant source of education, and whose ideas we have freely swiped. And if asked to explain the cause of an incurable case of mirroritis, we should blame it about 50-50 upon the continual lashing of Uncle Ephram's whip and the inspiration of early contacts with R.W.P.—*15 Allengate Avenue, April 1, 1936.*

Sub-diameter Tools

A Composite Chapter of Experiences

Prof. G. W. Ritchey, in *Astrophysical Journal*, Apr. 1909: Of much practical importance in its bearing upon the making of very large optical surfaces is the fact that, in the case of the 60″ glass, grinding and polishing tools of only about one-fourth of the area of the glass were used with entire success in excavating the large concave and in fine grinding and polishing; a full-size, flat grinding tool was used only in the preliminary work of securing a perfect surface of revolution. A circular grinding tool of cast iron 31½″ (80 cm) in diameter, was used in all of the fine grinding of the large concave surface. In polishing this concave, and in bringing it to an optically perfect spherical surface preparatory to parabolizing, a 90° sector-shaped polishing tool of exactly one-fourth the area of the large glass was used with the best results. In parabolizing, a circular polishing tool 20″ (50.8 cm) in diameter was exclusively used in securing the necessary change of curvature from center to edge of the glass; in addition to this the 90° sector tool, used with long diametrical and chordal strokes, was found to be of great value in smoothing out the paraboloidal surface. With these two figuring tools alone, used with the machine, a very close approximation to a true paraboloid was secured. The figuring was completed with much smaller tools used by hand to soften down several slight high zones.

In figuring the large paraboloid, one modification only was found desirable in the polishing machine described in my Smithsonian paper. The two cranks which give the motion to the polishing tools were remade in such a way that their throw or stroke can now be altered at will while the machine is running. The optician is thus enabled to change the position and stroke of the tool with a perfectly smooth progression while parabolizing; these changes are actually made at the end of each revolution of the glass, and a very great improvement in the smoothness of curvature of the paraboloid is at once apparent.

Harold A. Lower, San Diego: Ellison mentions that it is easy to grind and polish with small tools, but does not say how to do it. A 12″ Pyrex was rough ground face down for 9 hours over a 9″ tool. At the end of that time the curve had reached full depth at the center, as determined by measuring the sagitta, but lacked about an inch and a half of reaching the edge of the disk. (This first grinding face down leaves the edge of the mirror untouched—not even scratched.) When the curve had reached full depth in the center, the mirror was turned face up and the same tool used on top. One simply makes large epicycles all around the mirror, working mainly on the edge of the hollow, until the curve reaches the edge, at which time the curve should have become spherical. This grinding with the mirror face up also required 9 hours, but did not deepen the center the slightest bit, so it is important to go to full depth in the first grinding while the mirror is face down.

The fine grinding is all done with the mirror face up. The strokes used are large epicycles around the mirror, alternated with a zigzag stroke across the mirror. Do not permit the edge of the tool to overhang the edge of the mirror more than an inch or so, or a turned edge may result. One can tell when the surface is spherical, as the tool will slide freely in all directions. If it binds at any point, the surface is not spherical, and must be made so by working on the zone that binds until the tool will slide easily.

Polishing was done with a 9″ tool, with the mirror face up. The strokes used were large epicycles, alternated with the zigzag stroke. No difficulties with turned edge or zones were encountered, but it should be understood that good contact is just as important when using small tools as with full size. The handle of the small tool *must* be low and well centered.

A small tool, used on top of the mirror, tends to polish the center faster, and one must work closer to the edge than the zone that seems to need the most polishing. No pressure should be applied to the edge of the tool during normal polishing. It is, however, a very useful trick for removing a raised zone. Like HCF strips, applying pressure to the edge of a sub-diameter tool is "powerful medicine" and should be used with discretion. Pressure may be applied to the center of the tool, and will merely hasten polishing.

Figuring was done with a 6″ tool, working with a variety of strokes, mainly over the center. The figure is easily controlled, as one simply applies more abrasion at the points that seem to need it. I would not recommend this small tool method for any except short focus mirrors. For $f/6$ or shorter, it works fine.

Paul Linde, Crossville, Tennessee: The first time I tried a smaller-than-mirror tool was on a 12″ $f/4.5$. I used a 7″ tool merely because it was one I happened to have. The facets were graduated to fine points at the outer edge. The strokes should be of about the same length and of an elliptical or circular nature while making one round around the pedestal, and should be changed with every round to prevent formation of zones. As a general rule the center of the tool should travel more often over that zone or diameter of the mirror which needs deepening most. Starting with short, circular strokes close to the edge of the mirror and keeping away from the center, the strokes should be lengthened with every other round until they are quite long, after which they can be gradually shortened.

If there is a hill in the center it can easily be reduced by going with the tool across the mirror with slightly elliptical strokes, beginning with short ones and gradually increasing them with every second round. Turned up edge can be got rid of easily by pulling the tool farther over the edge of the mirror.

Of course, there can be no fixed rules for using the small polisher and one simply has to experiment and test often to see the results. Any mistakes made by the small tool can be corrected in comparatively short time by the use of the full-sized tool to bring the figure back to flat. I find the small polisher method by far the easiest way to get all the zones right, especially

with mirrors of short focal length. One word of warning: The mirror, when face up, is much more likely to be scratched.

G. E. Warner, Chicago, Illinois: There is nothing particularly new in the use of the small tool in working optical surfaces, nor is the method of working a mirror "face up" a novel one. In fact, practically all of the larger mirrors are made in this manner. Nearly all machine grinding and polishing is done in this way.

In working mirrors by this method it is the mirror blank, and not the tool, that is fastened to the pedestal. The manner of stroking is much the same as in the conventional method of hand working, but a certain precaution must be observed if dire happenings are not to result. It is imperative that the worker's walking around the pedestal or barrel be very regular. If it is not, astigmatism may be ground in, and it may or may not be ground out in the subsequent working.

One naturally wonders, in first contemplating this process, why the mirror will become concave, when with all of our previous experiences it was the upper member that became concave, while the lower one became convex. Let us suppose that in our grinding we use a straight, center-over-center stroke. Let us commence with a 4″ stroke—that is, when we are ready to start a forward stroke the nearer edge of the tool will be over the nearer edge of the mirror. The mirror, being 10″ in diameter and the tool 6″, a 4″ stroke will bring the farther edges of tool and mirror together. In making this stroke we cut a swath 6″ wide across the mirror, but leave the 2″ margins on either side of the mirror untouched. Also, the swath we have cut is deeper at the center. Now let us take another cut across the center of the mirror, at right angles to the first. Again we see the center of the mirror get the full abrasion, while the margins are untouched. With every change of direction of our stroke the same is repeated, and it becomes easy to see why the mirror will hollow rapidly at the center. In fact, the grinding is so rapid at the center that, except in the earliest stages of roughing out, the straight center-over-center stroke should not be used, as it tends to grind an irregular shape, usually one with much shorter radius at the center.

In practice the stroke used for all "excavating" may be a 4″, straight stroke in which the center of the tool passes over a point about 1″ to the side of the center of the mirror. This leaves a margin of 1″ of the mirror which receives very little work. If we should happen to overshoot the desired depth we can flatten the curve by stroking the mirror with the center of the tool, passing over a point about 1½″ or 2″ inside of its edge.

When employing this method of work, simply inverting tool and mirror will not cause the curve to reverse, and because we are able to control our curvature so nicely we may rough our curve out to its full depth.

In fine grinding, if we have roughed to the full depth, we shall have to choose a stroke that will not tend either to deepen or flatten our curve. A stroke in which the center of the tool traverses a point about 2½″ from the center of the mirror was found to obtain this condition.

As the fine grinding proceeds it becomes increasingly important that our

movement about the mirror, and our stroking, become as regular as possible, without employing mechanical artifices.

In work of this kind the abrasive mixture will not have much tendency to run off the edge of the mirror, because the latter is concave upward and liquids tend to flow to the center, hence it is possible to work in a much more cleanly manner than by the conventional method. The greater cleanliness in working leads to a greater freedom from serious scratches.

Great care must be taken in the fine grinding operations to see that all previous grade pits are removed at the margins of the mirror. The surface of the tool must never be used as a criterion for judging the completeness of any stage of grinding. Many hours of fruitless polishing can be saved at the expense of a bit of patience and thoroughness in fine grinding.

One of the first things that I am asked, when discussing the use of the small polisher is, "How on earth can you avoid a turned edge?" Let us look into the probable cause of turned edge in the conventional working of a mirror. Suppose our mirror to be at the end of its stroke. The pressure on the handle of the mirror in a horizontal direction tends to press the leading edge into the lap, because of the frictional resistance to the motion. This results in increased polishing at the very edge, and our notorious turn down results. This condition is augmented by poor contact between mirror and lap. Let us invert our full-sized mirror and tool and note the result of our reversal of stroke. If there is any tendency to "toe in," the tool merely tends to put the work on the mirror's face at a point far from the edge where, under ordinary conditions, it can do no harm.

The kind of turned edge we wish to avoid at all cost, because of the virtual impossibility of eliminating it once it is present, is that which is very narrow, yet so severe that it can be seen by casual inspection without applying any means of testing.

The strokes used in polishing are the same as those used during the fine grinding stages. A straight, elliptical, or zig-zag stroke of about 4″ length, with a center about 2½″ from the center of our 10″ mirror, may be used, and will result in an even polishing action and a regular figure. The tendency of the beginner is to try to avoid the edge entirely, in his efforts to avoid turning it. It is evident, however, that our tool must pass over the edge if the edge is to be polished. There is practically no danger of a bad turned edge if the tool is in good contact with the mirror, even though the tool may extend over the mirror's edge by nearly 3″.

A gradual turned edge of about 1″ in extent will naturally result from the polishing operation. It is possible to eliminate this by figuring.

In bringing the figure to a sphere from a more or less hyperboloidal curve, it was discovered that, by placing the edge of the tool over the crest of the curve and then applying considerable pressure with the fingers over that edge of the tool, the effect of a very small polisher was obtained. However, because the whole tool was still in contact with the mirror, the use of the tool in this way did not produce zones, as might be expected.

The broad turned edge previously mentioned, was treated in much the

same way. The TDE was about 1″ in extent. The tool was used so that its edge was about ¼″ from the edge of the mirror, with the pressure applied to the edge of the tool nearest the mirror's edge. The stroke was about 2″ long. In using the tool in this way it is rotated in the hands—just as in any other polishing operation. The pressure does not, however, move with the tool, but is maintained over the same zone of the mirror.

The local corrections were applied until, when spherical, the diffraction line could be seen all the way around the mirror while under Foucault test, even when the knife-edge had completely darkened the face of the mirror.

The parabolizing was done by means of the same localized pressure on the polisher. In this case the tool was placed on the mirror so that the edge to which the pressure was applied overlapped the center of the mirror by about 2″. The stroke used was about 4″ in length and zig-zagged back and forth across the mirror's face. Whenever it was noticed that any zone was not conforming to the rest of the curve as it developed, it was quickly whipped into line by proper application of local pressure to the edge of the tool. This manner of using the tool is not greatly different in effect from the use of honeycomb strips, except that it does not leave the sharp margins characteristic of the latter.

The use of this method of parabolizing permitted deepening the center of the mirror without disturbing the perfection of the edge.

The speed of grinding and polishing with a small tool should not be much different from that of full tool operation. While the area of the tool is less, the pressure which can be effectively applied is much greater. If the practical limit of size of a mirror which it is practicable to produce by hand work with the full tool is 15″ or 18″, it should be possible, by means of the small tool method, similarly to work a 30″ mirror.

For those who are afflicted with "dropsy," this method should have its attraction, for the valuable member—the mirror—is securely fastened down and the hazard of fatal termination due to gravitational attraction is mitigated.

All in all, I would suggest that telescope makers add this mode of operation to their repertoire. If it does not replace the "biblical" manner of operation, it certainly should prove a most valuable adjunct.

Horace H. Selby, California: Although sub-diameter tools have been used for the past few years by this scribe, in the construction of a triplet refractor objective, a paraboloid, two Hindle spheres, 20 flats and two photographic anastigmats, he will not attempt to write on the use or manipulation of such items. One TN will deepen a surface with a stroke which, in another's hands, will make a similar surface less deep. Of course, if all the many variables of any one polishing or grinding operation could be rigidly controlled, evaluated and understood, this operation could be performed and repeated "ad nauseam" and the end results would always be the same. Then art and craftsmanship would change to science, and results could be attained in a straightforward, mathematical and very satisfying manner.

Since the *use* of small tools will not be discussed, the only thing remaining as an excuse for these comments is the subject of construction.

Glass tools are more popular with amateurs than are tools of any other material. Professionals, however, use tools of wood, artificial resins, cast iron, sheet steel plus glass, brass, lead and boiler plate. Of these last, wood is cheapest and most easily formed; so consideration of it is most heartily advocated.

Of the physical properties of wood, the most important, from the standpoint of the TN, is probably the elasticity modulus, which is a measure of the rigidity. The approximate moduli for the most suitable woods are:

Yellow birch (*Betula lutea*) 2,000,000 lbs. per square inch.

Shagbark hickory (*Hicoria laciniosa*) 2,200,000 lbs. per square inch.

Black locust (*Robinia pseudoacacia*) 2,100,000 lbs. per square inch.

Sugar maple (*Acer saccharum*) 1,800,000 lbs. per square inch.

Of the above, the writer uses sugar maple, well dried, because of its ease of working, small tendency to warp, and availability.

The rough lumber is smoothed, planed to the proper thickness, sawed into circles, mounted on a lathe and cut to curve with a wooden template covered with abrasive paper. These operations are quickly performed by the local planing mill, and entail but small expense. If used for hand polishing, the tool is now ready for the pitch, which is poured, formed and faceted as usual. Since the tools are to be used on top of the work, no paraffin or other treatment is needed. For machine polishing, a metal plate may be screwed to the back, with the usual provision for driving attached. As with metal tools, the force may be applied much closer to the worked surface than when glass is used.

When tools are wanted for grinding, the same construction is used, except that the pitch coating is very thin and squares of glass or of metal are used to cover the tool.

Some workers dip tools of glass into warm water before polishing. This is not feasible with untreated wooden disks; so resort may be had to cheap radiant electric heaters of the reflector type. By holding the heater close to the tool, and revolving the latter, the pitch can be softened quite rapidly. This operation, when used in first forming and cutting the tool or when applying metal or glass facets, is a great saver of time.

Satisfactory dimensions for polishing tools are:

Thickness of wood	1/6 diameter
Width of facets	1/6 diameter
Width of channels	1/18 diameter
Thickness of pitch	1/36 diameter

Sizes will vary, of course. As an example, five tools were used in making an *f*/2.3 paraboloid, 12½″ in diameter: 2″, 4″, 6″, 10″ and 12″.

The use of wood polishers is by no means new—Ritchey used them years ago at Yerkes, and many professionals use them for some types of work now. To date (1936) no other users of wooden grinding tools are known to the writer, who prefers them for Carborundum No. 400, No. 600 and emery.

Making and Using Metal Laps

By R. E. Clark
Langeloth, Pennsylvania

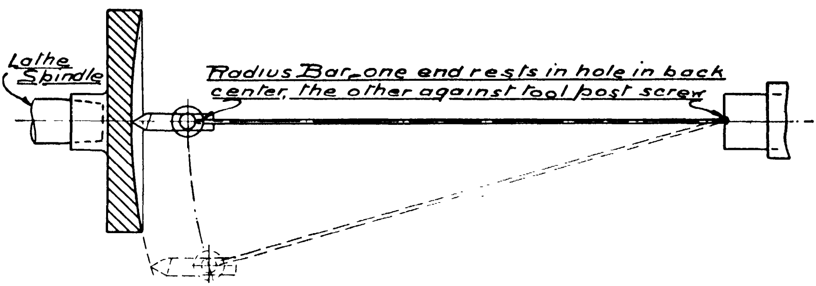
Concave Tools: The making of small cast iron tools has presented many difficulties to the average amateur. It is especially hard to get a perfectly spherical surface when using the ordinary right angle cross-feed as found on an engine lathe and, unless one has unlimited patience and skill, the use of hand tools on metal surfaces is almost out of the question.

The following method will give consistently good results, and while perhaps not new, is probably unknown to most amateurs.

The metal blank (cast iron or brass) is first completely finished on the back side and placed on a tapered mandrel in the lathe spindle. A light, cleaning cut should be taken across the face.

A ¼″ round rod is cut to the exact length of the radius desired for the completed tool, and the ends are ground and filed to a blunt point.

The point is ground off from an old lathe center (a new one may be made



All drawings by the author

FIGURE 1

Plan of set-up for concave tools.

up if desired) and a ¼″ hole is drilled ⅛″ deep in the ground end. Place this center in the tail stock of the lathe (Figure 1).

Place one end of the radius rod in the hole in the back center, and rest the other end on the tool-post screw, directly above the tool holder. The axis of the rod should be coincident with the axis of the lathe.

Using the cross-feed screw, run the lathe tool toward the periphery of the lap that is being made, stopping at a point about 1″ from the center. Lock the tailstock to the lathe bed and, using the tailstock screw, feed the lathe tool point into the face of the lap. The forward movement of the screw is transmitted through the rod to the point of the lathe tool. Up to this point in the set-up the main slide should be free to move along the lathe bed; now, however, the main slide lock should be lightly clamped to the lathe bed, so that the longitudinal movement, while still fairly free, will be somewhat retarded. This will prevent the tool from feeding into the work too freely.

With everything set, start up the lathe and, using the cross-feed screw, feed the lathe lap across the tool toward the center. On the completion of this first cut, move the lathe tool point back toward the edge of the lap ½" farther than the start of the first cut. Continue successive cuts until the edge of the lap is reached.

The final cut should be very light, made with a round-nosed tool and fairly high speed. Good finish is essential.

Convex Lap: A flatplate *A,* Figure 2, is clamped across the lathe bed as near the headstock as possible. A post *B* sticks up from this, on the center line of the bed, so that its top is slightly above the cross-slide.

A hole *C* is drilled and tapped in the cross-slide, in such a position that, when the lathe tool is at the center of the lap, the hole will be on the center line of the lathe bed.

A piece of flat iron is drilled with two holes—one to fit over the post *B*

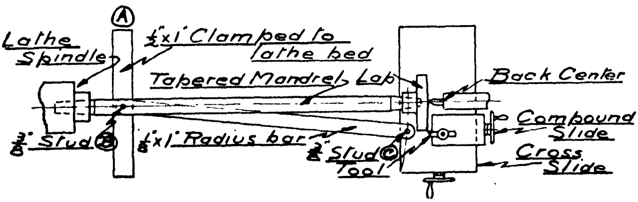


FIGURE 2

Plan of set-up for short radius tools.

and the other over a stud screwed into hole *C*, the center distance of these holes being the required radius for the tool being made.

A mandrel is made, with a taper on either end and having such length that, when one end is inserted in the lathe spindle taper and the lap blank placed on the taper on the other end, the back center may be run into a center hole on the face of the lap.

In using this rig the cut is started an inch, more or less, inside the periphery of the tool, and each succeeding cut is started slightly nearer the center than the preceding cut—all cuts, of course, being made from the center outward. The compound screw is used for feeding the lathe tool into the work.

So much for short radius tools. On longer ones I proceed as follows: A simple calculation involving our old friend the sagitta formula $r^2/2R$ ("A.T.M.," page 312), in which r is the radius of the lap and R its radius of curvature, gives us the depth of our cut. For example, required the depth of cut at center on a tool 5" in diameter and having a radius of curvature of 165" (a radius of 150" to 200" is often found on the fourth surface of an ordinary achromatic). Substituting in the formula, we get .019". For practical purposes .02" will give as good results.

The tool is set up on a mandrel in the lathe spindle and a cut is taken

over the face. Run the slide rest back and, with a scale and pencil, divide off the face into 10 or 20 equal spaces (Figure 3). Start at the center and end at the edge of the tool. Thus, 20 spaces each ⅛″ = 2½″, the length of the radius of this particular tool.

Run up the slide rest and, with a scratch awl or pencil, make a series of concentric circles over your markings.

Your compound slide is then set parallel to the lathe bed, the lathe tool placed at the edge of the tool and the cross-slide clamped.

Most compound slide screws have 10 threads per inch, with a micrometer head divided into 100 divisions. Therefore each division is equal to 0.001″.

Our total depth is .020″, therefore if we advance our lathe tool in 10 or 20 (depending on the number of concentric circles we have marked off) uniform steps of .002″ or .001″, we should arrive at a stepped surface approaching a curve. Very little hand work with a wide-faced hand tool will smooth

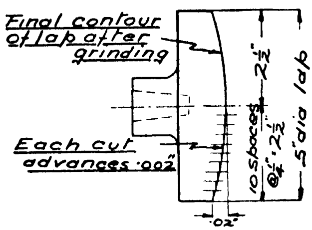


FIGURE 3

Cutting long radius tools.

up the surface, and by the time you have run your glass through the 80 and 220 stages the surface should be almost exactly right.

In making up these long-radius tools, I usually make them up in pairs, using exactly the method as outlined above for the convex tools, except that the cut starts at the center and finishes at the edge. A few minutes' grinding with 220 will put them in perfect contact (test with pencil marks).

It is absolutely paramount to work with exactitude when doing optical work. The average amateur has little conception of just how exact lens surfaces must be for good results. The final figure of long-radius fourth surfaces should always be tested both for focal length and figure. A slight deviation from the exact prescription will spell the difference between a good achromatic and an exceedingly poor one.

Moral—Take time and have patience.

ON USING METAL LAPS

While it has been the custom to make small lenses by means of ready formed metal tools, their use for working lenses and mirrors of longer focus has not (at least among amateurs) been so general.

Prior to the invention of silvering on glass, by Liebieg, all mirrors had

of necessity to be made of material which in itself was capable of taking a high polish. The softer metals (speculum metal, etc.) were practically the only materials which would fill all the requirements. These metallic mirrors were usually worked on metal tools which had been turned in a lathe and smoothed by grinding on a mating surface, the curve being gaged to a spherical template.

This was the generally accepted method of making a speculum prior to the middle of the 18th Century. The invention of the Foucault test greatly simplified the mechanics of mirror and lens making. In that the skilled fitting of the lap surface to its mating shell did not have to be nearly so accurately done, the faults of the semi-polished surface could be seen and corrected as the work progressed; prior to this test nothing much could be done toward correction until the speculum was actually tried on the heavens.

One outstanding reason for the use of glass for tools is its cheapness. Any old piece of glass which has the necessary thickness and diameter can be and is so used. Most amateurs make only one mirror of a certain size and focal length, therefore it would be foolish to go to the extra expenditure of time and money to fabricate metal laps. There is, however, a class of amateurs (heaven help them) who are no longer satisfied to do things in an amateurish way. Poor souls, they are never at rest and must forever be trying some new (or old) stunt. It is to these few who are so deeply steeped in iniquity that the following remarks are dedicated.

In my chapter on the small lens I take the reader through the various steps actually used in fabricating a definite piece of optical apparatus. The same procedure will be followed here, a 6″ diameter, *f*/8 mirror being chosen, although glasses up to 12″ diameter can be and are successfully run by the following method.

Procure two soft iron castings (Meehanite by preference) of such diameter that they will finish up 5½″ O.D. Finish the surfaces as closely as possible to the desired template. Grind together on your spindle with 220 Carbo until the pencil mark test shows that the surfaces are truly spherical. The focal length of the concave can be tested, using the knife-edge in the ordinary way, adjustments of focal length being made by reversing the laps on the spindle. The top tool (or the glass) is in this method allowed to spin freely on a pin, exactly the same as is described in my chapter on making small lenses.

Speed is important, and should be such that your grinding compound will not be flung violently from the edge of the tool; 140 to 160 r.p.m. is the upper limit for a 5″ to 6″ tool. If larger tools are used the peripheral speed should be cut down in proportion. The important thing is to keep the Carbo on the tool—not on the side of the splash pan.

Make up a runner (brass or cast iron) 3″ in diameter and 5/16″ thick. Warm your glass blank (Pyrex, preferred) and, with either pitch or Chaser's cement, stick the runner on the back of the blank, center carefully with a pair of dividers or hemophrodite calipers and allow to cool.

In order to save the finished tools, I usually rough out the major portion

of the glass on an old tool of about the right curve, using No. 60 or 80 Carbo, or else, after I have turned up the convex tool, and before it is ground true on its mate, I use it as a roughing tool. A lot of retruing of laps will be saved by this procedure. Wash up everything very carefully. The pin bar and fingernails are both favorite places for Carbo to roost—so watch them.

Change over to 220, running your curve about 12" longer than required (test with a light). Get a good surface, but do not worry if your pencil contact between glass and tool is not 100 percent. Wash up again.

There is no good reason, when using a mechanical spindle, for using six or seven grades of Carbo, as in hand-work, since even the finer grades cut very fast and 220 pits will disappear in a few moments with 3F or even 400 Carbo.

The ordinary wet lasts from 30 to 60 seconds. One precaution, however, must be observed in changing your grades: between each grade run your concave tool for at least two or three good wets on the top of the convex. In other words, alternate your grinding on the convex between the concave tool and the glass. Only in this way have I succeeded in maintaining the curve of my convex and also good contact between it and the glass.

I invariably finish with 6F or 906, mixing with either 10 or 15 percent of ordinary talcum. A good, safe stunt, and a saver of scratches with this fine grade, is as follows: Apply with the finger a good dab of dampened compound to the center of the rotating tool and spread it as evenly as possible. Then, starting at the center, hold a piece of glass in the fingers and work the compound evenly outward toward the edge. Using a "bruiser" in this manner will eliminate any chance of a particle of Carbo scratching your mirror. Stop the spindle and put the mirror on the tool, start up, and spin out the wet. Do not try to put the glass on the tool when it is revolving —sure disaster will follow. Always give at least 10 or 12 (20 is better) wets of this last grade, thus insuring freedom from pits. Run as dry as you can—your earlier grades may be wet, but in order to get a really fine surface this finest grade should be run as dry as possible, short of sticking. Wash up.

Polishing: Preliminary polishing should be done on HCF. Dry your tool and apply with an old knife blade a very small quantity of "stickum" (heat some pitch and add turpentine until the cooled mixture will just stay solid). Start your spindle and, with your knife blade, apply a piece of stickum the size of a pea to its center. Bear down hard and spread the dope evenly and thinly all over the tool surface. Do not use too much stickum, as a thick layer acts as a lubricant and your HCF will slide around under the heat generated in polishing.

Cut a circle of HCF 4½" O.D., warm slightly and press directly on the doped convex. Use your palms and press hard. Next, lather your hand with ordinary soap and water and go over the HCF surface (incidently, the lathering may help to get some of the stickum off your fingers).

In polishing, I would advise as high a speed as possible. Personally I

use from 1500 to 1800 r.p.m. Use very dilute rouge and on no account allow the HCF to get dry. After five minutes' polishing remove the lap and glass, and cool thoroughly under the faucet. Three or four 5-minute polishing spells (with cooling between) should polish your glass clear to the edge. Do not apply too much pressure—it simply spoils the lap and does not seem to speed up the operation.

Final polishing and figuring must be done on a pitch lap, by hand. I have tried to figure on the revolving spindle but have never yet been able to escape very serious zoning. It is probable that your first few attempts will result in badly zoned surfaces, and only by repeated trials will you arrive at a combination of stroke and pressure which will result in a good spherical surface. Final figuring, as noted above, must be done on pitch and by hand.

It sometimes happens that the outer ½″ of the glass will refuse to polish out on the HFC lap, this fault can usually be traced to insufficient fining by emery and not, as thought, to the small diameter of the HCF surface. If the HCF is made larger than the 4½″ diameter, the bugbear of turned edge will surely develop. Also, if the glass is fitted to run on the spindle and the 4½″ polisher run on top, turned edge will result. Small polishers are hard to control, if allowed to spin freely on top of the glass—the cutting is very erratic, taking place sometimes on the inner edge and sometimes on the edge nearer to the outside of the spinning glass. Rose laps are also very uncertain in their action when allowed to spin freely.

Making a pitch lap by the "dunking method" (described under flat laps, in the article on small lenses) is very easy, and the final polishing and figuring by ordinary hand methods is not too arduous an undertaking for even the poor, jaded mirror maker who had hoped to escape a little hard manual labor by turning to metal tools and a mechanical spindle.

[Editor's Note: In addition to the practical data given by Mr. Clark in his chapter, some pertinent points were contained in his private letter of transmittal—so much to the point did they seem, in fact, that permission to add them was asked. With that permission Mr. Clark gave the warning that he does not pose as an expert, and added that, by definition, an "expert" was any one more than 20 miles from home. He had been asked three questions and these, with their answers, are arranged as follows:

Q: "Just why is it that people want to use metal tools?"

A: "It appears on the surface to be easier than using glass for a tool. As a matter of fact it is much harder, and I cannot say that it saves very much time. It is, however, less fatiguing, and there is a certain fascination in doing a thing mechanically in place of by hand."

Q: "Can metal tools be used in hand work, like glass tools?"

A: "They can, but there is no real advantage; in fact, there are several disadvantages, chief of which is the inability to maintain good contact, due primarily, I suppose, to the unequal hardness of the two surfaces."

Q: "It is often stated that a lead tool gives a finer finish than a glass tool. Is this the case and, if so, can you say why?"

A: "If one will put a lead finished surface and a glass finished surface together under a microscope, get the light right, and put on 75X or 100X, one will find no difference between them—though the lead will more quickly give the same degree of finish. But the pits on the lead-finished surface, seem to have their sides covered with a film of lead, which I think gives the satiny appearance when the surface is looked at without magnification. The same thing is true of a surface finished on brass—the extra fineness is more apparent than real."

Considering the discouragement just quoted, why should the chapter then have been included in the book at all? One reason was that the discouragement is not complete or categorical, and the other has to do with human nature; it was Mark Twain who said, "There is a great deal of human nature in man." Many wish to try a thing, just to know about it, and even if they suspect in advance that they will not like it very well. For the rest, see the final paragraph on page 65, "A.T.M."

Lead tools may perhaps be made by casting. R. L. Beardsley of Los Angeles tells how he attempted this by making a plaster of paris cast of his mirror, and then a positive cast of that, and poured the molten lead on this. "But it boiled and bubbled," he says, and he adds, "it is difficult to make a good lead lap that way." Another way that has often been used is to hold a disk of lead in the hand and whack it with a hammer. When this method was tried, Mr. Beardsley states, "the other side gradually assumed a convex shape which could finally be scraped close enough to form to start grinding." James E. Myers of Omaha states that he uses iron tools for roughing out and, for fine grinding, "soft lead about ½″ thick, sweated on a steel plate of ½″ thickness. Above all," he adds, "don't forget to tell the boys to channel them, just as in the case of a pitch lap, otherwise there will be trouble. We face the lead laps in the lathe and then mount them on the spindle, use a flat scraper and shape them to about 2″ longer radius than is required by the mirror, and then channel them."]

Metal Mirrors and Flats—a Composite Chapter

[Editor's Note: As glass has a better working disposition than metal, only relatively few amateurs have occasion to make optical surfaces on metals. That minority, when definite data is wanted, find it difficult to secure. Metal mirrors went largely out of style when Liebig found a way to silver glass. But a number have been made in more recent years—sometimes for a special purpose, sometimes for the fun of trying something different, perhaps in some instances "just because." The worker is thrown back a long way, on the writings of the old-timers, such as Newton (in the *Philosophical Transactions,* Nos. 80, 81, 82, 83, 88, 96, 97, and in his "Opticks"), Smith (in his "Opticks," Vol. II, pages 301–312), and the younger Herschel, Sir John (in "The Telescope," pages 126–178). None of these is modern. Two modern experimenters and workers are known to be planning papers or small books on this subject; possibly by 1937 or 1938 these will be available.

In these circumstances each worker has been forced virtually to re-invent the art by himself. There are quite a few differences between the technics of working metals and glass, a fact which will be discerned in the several separate communications which follow. It is hoped that the homely experiences presented will forestall further running up at least some of the blind alleys.

Not everything regarding this work, noted in sulphurous private communications, can be quoted, as this book must be maintained fit to print. One metallurgist writes that, after months of experimentation, he finds that "every metal examined by him has surface flaws, in addition to the well-known physical defects. Even at magnifications as low as 50, the polished surface is seen to be more or less covered with tiny pits. These pits are distinct from the non-metallic inclusions and other impurities inherent in steels. Some mirrors from ancient telescopes, which were similarly examined, showed the same surface imperfections in the speculum metal."

Messrs. W. Ottway and Co., Ltd, of London, who make and sell stainless steel mirrors, mention that greater care must be used in all the operations of working them, especially in the final stages of polishing, "where practically a dustproof room is required."

Despite the difficulties stressed above and elsewhere, metal mirrors will doubtless be made by a number of workers.]

Casting speculum metal, by C. M. Saeger, Jr., Chief of the Experimental Foundry Section, National Bureau of Standards: Castings of speculum metal are composed of 66.6 percent of copper and 33.4 percent of tin. By increasing the copper content the color shades gradually into a yellow and with a larger content of tin into a blue. With an increase in the content of tin, aside from the effect of changing color, the alloy becomes very brittle and cannot be handled satisfactorily. Good speculum metal should be perfectly white without a tinge of yellow, have a fine grained fracture and be sound and uniform and sufficiently tough to permit grinding and polishing without danger of breaking. In regular foundry practice, considerable

difficulty is encountered in producing a speculum metal casting having a cast surface satisfactory for polishing and free enough from excessive internal stresses so that the castings will not crack while cooling in the mold or while being polished. Development of the proper foundry technic has required considerable experimentation in order to overcome these difficulties.

A procedure giving satisfactory results consists in melting the virgin copper in a gas-fired crucible furnace under a cover of charcoal, and adding the tin when the copper is molten. As a result of a considerable amount of experimenting it was decided that one half of one percent of zinc should be added to the molten metal as a deoxidizer before removing the crucible from the furnace. The metal is cast at a temperature of approximately 950°C, the exact temperature depending upon the size of the casting. Green sand molds made from a grade No. 00 Albany molding sand are used, the surfaces of which are coated with a mixture of rubber cement and Ceylon graphite, as the ordinary mold facing materials have not proved satisfactory in producing smooth surfaces on the completed casting. The metal is allowed to cool in the sand mold sufficiently for solidification, and then it is removed and placed within a hot furnace in which the metal has been melted.

The castings are allowed to remain in the furnace until the castings and the furnace have cooled to room temperature. This slow cooling insures a minimum amount of internal strain which under ordinary treatment causes the cold brittle casting to break.

Prof. Arthur Howe Carpenter, La Grange, Illinois: In the ordinary sense of the word "alloy," speculum metal is not an alloy. It is an intermetallic compound, Cu_3Sn and a mixture of solution of either more tin or more copper than just this composition which corresponds to about 38.5 percent of tin. Metallographers are calling these mixtures "secondary solid solutions." They do not have real "metallicity" and are very hard and brittle. The essential point is that every grain or crystal of them is like every other grain or crystal, and there are no parts of them harder or softer or different from any other part.

"In the search for alloys I think there is a hint in this fact, and that we should look for alloys of this kind. Naturally, the alloys that are not brittle are more attractive, but they have intrinsic properties that make it impossible to work them successfully to a fine surface. The grains are not alike, but differ from grain to grain, even in the most thoroughly annealed 'solid solutions' which is the type of Allegheny Metal.

These plastic metals will "work-harden" in the case of polishing and would give a great deal of trouble, as they would not harden uniformly and graininess (a lemon peel effect) would develop. A mass made up only of "intermetallic" crystals would not do this. These crystals would be just about as hard as they could be already and would be non-plastic like diamonds, although not so hard. Most pure metals are plastic, and so are the kinds of alloys known as "solid solutions," but true chemical compounds, like ordinary salt, are hard, brittle and unyielding, *i.e.*, are non-plastic.

Copper and zinc form a similar compound containing about 60 percent brittle zinc of about the formula Cu_2Zn_3, with either more copper or more zinc than just this composition. It is as brittle as glass and very white. It takes a high polish. I do not know about copper and aluminum intermetallic compounds, but it is possible that some of them might prove better than many others. I am sure that a research into this field might develop or open up compounds that might be a real advancement. Several have been proposed along this line.—*811 Bell Avenue*

Experience of L. G. Bostwick, New York: The metal reflector that I have is made of "Allegheny Metal." This material is a chrome-steel and is very tough. After trying many methods of roughing it out, including grinding on glass, cast iron, cold-rolled steel, and lead, and making little progress, I finally succeeded by grinding on the side of a Carborundum wheel, using the wheel as a tool fastened to a bench in the usual way. Fine grinding was done on very hard pitch, and polishing on beeswax. A very fine polish was obtained which, for two years, showed no visible deterioration. Temperature effects during polishing and at any other time were entirely absent, as far as I could determine.

After spending many months on the work, and figuring the surface to a very good parabola, I discovered that the metal had not been properly annealed. The metal was under strain and a slight tap made the figure worthless. I have since had the metal thoroughly annealed. This ruined the surface and I have not yet brought it back to a good polish.

You may imagine that the series of disasters that I went through affected my enthusiasm for the metal mirror, and consequently my time recently has been spent on a small refractor. I expect to finish the job later, however.

Experience of Paul A. Chamberlain, Chicago, Illinois: It is well known that the coefficient of expansion of steel is .00001099; whereas that of glass is .00000954. The difference is .00000145. The heat conductivity of steel, being .109 compared with that of glass which is .003, permits the steel to conduct the heat 36 times faster than glass.

I used Carpenter Stainless Steel No. 5 [Carpenter Steel Co., Reading, Pennsylvania.—*Ed.*]. The particular piece I used was forged to a size 8¼″ in diameter and 1″ in thickness. I machined the disk to a diameter of 8″ and a thickness of ⅞″, and faced it off to a radius of 100″. Usually it takes a long time to grind an 8″ glass disk to a 100″ radius, whereas I was able to machine the disk from a plane to a curved surface in a few hours.

After three hours of manual grinding with No. 80 Carbo, tool marks were still visible. At this rate grinding would have taken approximately ten hours, so I tried grinding the disk on the lathe, with the disk turning and the tool moving across, supported pivotally on the tool post. This removed the tool marks from the disk in two hours. The radius of curvature was then 72″. Nine hours of additional work finished the rough grinding, with the radius 68″. I found that grinding with No. 80 Carbo caused a bad roughness about 3/16″ from the edge, due to the grains of abrasive rolling in

at the edge before breaking down. This does not happen with glass, as the grains break up without this rolling in.

I continued two hours on the lathe with No. 180 Carbo, resulting in a radius of 73″. One hour more with No. 180 Carbo was then followed by three hours of No. 320, which gave a final radius of 70¼″, before fine grinding.

Four hours of fine grinding with No. 600 resulted in a curvature of 70″. At this point I tried polishing, but the surface was badly scratched. It is necessary to wash the No. 320 and No. 600 Carbo. Both sizes contain a few large grains, which is the cause of the scratches. When grinding glass these larger grains are broken down near the edge and thereby cause no harm, but with metal the grains bury themselves in the soft tool (cast iron) and project high enough above the surface to cut a groove in the disk. They start as scratches and end with abrupt holes. The explanation is obvious: the shaving of steel builds up in size ahead of the grain.

At this stage I encountered many trials and failures. First, I tried HCF with No. 600 Carbo. This produced a humpy surface. I next made a hard pitch lap and, after four hours of grinding with No. 600 Carbo on the lap, this appreciably diminished the humpy condition and all the outstanding scratches were finally removed, though the humpy condition persisted.

I continued the fine grinding on the cast iron lap, using the same size of Carbo. After one hour only very fine scratches were visible. I finally accomplished my best results by using Aloxite abrasive. (This was before I tried the washed Carbo, as mentioned above. I also used washed Carbo on the chrome-plating, with very good results.) This proved to be softer than Carborundum and it did not scratch nearly as much. It also produced a finer surface. The Aloxite abrasive grains break down easier than Carbo and do not produce deep scratches, but the Carbo grains bury themselves deeply in the tool and cut scratches in the mirror. One-half hour of polishing on the pitch lap with Aloxite produced a figure with a slightly elliptical curve. Another half hour of Aloxite on the pitch produced a curve with a small spherical surface in the center.

I then polished an additional half hour, bringing the total of polishing with Aloxite on pitch to 1½ hours. A spherical surface, which gradually worked out from the center to the edge, was the result. Elated over this outcome, I continued polishing with Aloxite on pitch for six hours, which produced a good spherical curve and reduced the turned edge to ½″. It was my hope at this time to resort to a finer degree of polishing. At first I tried rottenstone but found it too soft to produce results. After correcting the turned edge, which required two hours, I attempted to use rouge. This caused a hollow to appear in the middle, proving that the steel was not of uniform hardness. The hollow that first developed in polishing was misleading, because of the 1″ hole bored through the center of the disk. At that time the hollow zone around it was credited to the presence of the hole.

It was necessary to resort to fine grinding, in order to remove the central

hollow zone. This helped, for the time being, to correct the previous mishap. The curve rose high in the center. This was easily removed by fine grinding on the cast iron tool, with No. 600 Carbo, which brought the desired spherical curve.

I then returned to polishing with rouge. A deep hollow appeared, as before. However, I now prolonged the polishing, in order to experiment and observe, as I felt that there was something I needed to know at this stage. Extensive polishing produced a deep hollow, similar to the bottom of a saucer. I concluded that a soft center in the steel was what made it impossible to polish uniformly. Probably more careful heat treatment of the steel disk would have prevented this.

I decided to produce an evenly hard surface by chromium plating. Of course I first had to regrind. Washed Carbo was again used, followed by repolishing. The plating gave the disk .004″ of additional thickness, but it also produced an increase in thickness at the edges, which were as much as .0052″ higher than at the major part of the surface.

It took five hours of fine grinding to bring the chrome-plating to the proper curve, and the polishing required another ten hours. The resulting surface revealed a slight turned edge, around both the center and the periphery. I corrected this by local polishing on the lathe, with a tool of triangular shape. By testing every three minutes I was able to follow the progress made in correcting the turned edges.

The turned edges that result from polishing or grinding seem to be characteristic of chrome alloys as well as the hard chrome-plating. This seems to be caused by the heat generated, possibly due in part to the weight of the metal, softening the lap. The leading edge is always sliding up a slight depression [Everest's "plowing in."—*Ed.*], resulting in a turned edge. I have been unable to remove this fault using a modified lap, and the only alternative was to try local polishing on the lathe, which worked very well.

The steps in developing the polished curvature on the secondary mirror were identical with these used in the larger mirror. I machined, ground and polished soft, a piece of similar steel of 2″ diameter. The surface was a poor match, compared with the chrome-plating on the larger disk. The surface was pitted, dull and soft when compared with the shiny chrome.

After grinding the secondary to a correct curve I had it chrome-plated (.002″). The plater buffed the surface of the secondary and produced a very (?) nice turned edge. It is necessary to guard against these well-meaning efforts of the plater, by telling him very forcefully not to do anything to the surface of the mirror, other than plate it.

In summary:

1. Forty hours of grinding and polishing spent before hollow in center showed up.

2. Total time on tool for grinding, polishing and figuring the chrome-plated surface, 30 hours.

3. Tested curvature every three minutes while local polishing.

4. Figuring required 15 hours.

5. Mirror finished correctly to approximately 95 of r^2/R.
6. Possible error ½ millionth of an inch.

—*8054 South Honore Street.*

Experience of J. D. Beardsley, Washington, D. C.: While employed at the Naval Research Laboratory, I was assigned the task of making an 11″ astronomical mirror of stainless steel, for a naval expedition to Fairbanks, Alaska.

Many stainless steels such as 18 chromium, 8 nickel are described as "austenitic." This means that they are non-magnetic and that the iron is not in the ferritic condition. When such steels are turned or abraded the surface becomes martensitic, causing a very marked increase in hardness, thus covering the face with a film having different physical characteristics. Steels containing nickel have, in addition, a yellowish tint. For these two reasons nickel steels, or any austenitic steel, were ruled out from the beginning.

Consultation with Dr. R. H. Canfield, chief metallurgist for the laboratory, guided to the selection of Carpenter's No. 5, containing approximately chromium 13 percent, carbon 0.1 percent, and zirconium sulfide 0.25 percent, with the remainder iron. The addition of the zirconium sulfide makes the material comparatively free-machining. A square blank was purchased, 12″ by 1¼″ thick.

To start with a flat piece of material, and "hog" out the curve with Carborundum or emery would be almost impossible, even with a machine, as this metal abrades perhaps 100 times more slowly than glass. It was necessary to cut both the blank and the lap to approximately the correct curve. This was done by laying the curves out on pieces of flat sheet steel ¼″ thick, which were used to guide the transverse feed on a lathe, in conjunction with a roller and weight. This was done after the blank had been cut circular and the back had been trued.

The lap was placed face up on the grinding machine, the mirror face down. A wooden handle was cemented to its back with medium DeKhotinsky cement. This handle was provided with a hole to accommodate the machine stroke bar pin. Roughing was begun with No. 60 Carborundum, using a long stroke and 40 pounds' weight. After the blank and lap showed uniform abrasion all over, except for the outer 1/16″ of the mirror, No. 90 Carborundum was substituted and the stroke was reduced to about 7″. After all pits from No. 60, which were quite deep, were ground out and the edge had disappeared, the abrasive was changed to No. 220 and the stroke shortened to ⅓ of the diameter of the mirror. The grinding with this grade was continued until mirror and tool fitted quite perfectly.

The machine and the room were then carefully washed, and all Carborundum was removed from the immediate vicinity. Grinding was then continued with American Optical Company's emery M302, using a ⅓ diameter stroke and no weight. At this time, scratches began to appear despite precautions, so a lap made of tin and lead, backed by a 1″ brass plate, was turned and fitted to the mirror by means of prussian blue and hand

scraping. By using care with this fitting it was possible to continue the grinding without going back, though several hours were consumed in bringing the lap to a perfect fit using, 302 emery.

At all stages of the grinding up to this time the blank always looked black, due to charged abrasive, so instead of continuing with emery, glass powder was substituted. This powder was mixed with water and a small amount of glycerine, and after settling for 30 seconds the top inch was siphoned off, after 30 seconds more the next inch, and so on. In the same manner 2-, 10-, 30- and 60-minute glass powders were prepared. Before beginning this grading it was determined that M302 emery settled about 1″ in 30 seconds.

Grinding was now begun with the 30-second glass powder. The lap lightened considerably in color but the mirror turned from a very dark to a very light gray, and the fine, sharp pits began to show an iridescence. When the mirror had acquired a uniform appearance, its outer zone was examined with a low power magnifying glass, which revealed the presence of a few pits left from the 220 Carbo. These were entirely ground out with the 30-second glass powder before changing to the 2-minute grade. After this stage the difference in the sizes of the pits between 2-, 10- and 30-minute abrasives is quite impossible to determine, as the surface reflects considerable diffused light. It is accordingly necessary to trust to judgment with these fine grades, using with each one a shorter and shorter stroke, and doubling the grinding period with each reduction of powder size. Although 60-minute emery was prepared it was not used, because the grinding period had become eight hours or so with the 30-minute and, needless to say, patience had shortened with the stroke.

The polishing was begun on a pitch lap, prepared in the ordinary manner, described in "A.T.M." for glass, using rouge mixed quite thin. The pitch was made by cooking plain roofing tar until, at room temperature, it could be dented by the thumbnail only with difficulty. During the course of the polishing honeycomb foundation backed by a mixture of rosin and beeswax was tried. This material had a very bad way with the mirror, making it look like a cobblestone street, when given the Foucault test. A great deal of difficulty was experienced with the rouge, as some chemical action seemed to take place, causing the surface of the mirror to have brown spots and rings, which were quite rough, entirely spoiling its appearance. Polishing was continued, nevertheless, until all abrasive pits were removed, in the hope that the spots would disappear. They moved about the surface but were there at the end of the rouge polishing. Mr. G. H. Lutz, who was with Dr. Ritchey at this time, working on the Naval Observatory's 40″ mirror, suggested mixing liquid soap with the rouge. This was tried but it did not remove the spots. Whiz Metal Polish was tried. It removed them, but scratched and etched the surface. Polishing was now resumed with the soapy rouge mixture, in order to remove the scratches and etching. The brown spots reappeared, though in not so pronounced a manner. Dr. Canfield suggested zinc oxide, at this stage, to remove the spots. This

material worked slowly but scratched very slightly, due to the fact that it was not carefully washed. After the spots were nearly gone, Higgins' India Ink was used as the polishing medium. The fine carbon particles seemed to have sufficient hardness to cut very slowly, and they left the surface as smooth as water and as bright as a new silver coin.

During the extensive polishing the figure was occasionally observed. Due to careful grinding it was nearly spherical at first, but became deeply hyperbolic later. This was corrected by inverting the mirror and lap, after removing the handle. By using the full size tool with a ⅓ diametrical stroke the mirror was brought back to a sphere. This figure correction was made while still using rouge, as the other things tried cut too slowly. All polishing with zinc oxide and india ink was done with the mirror face up. This is advantageous for two reasons—one that the polishing material does not run off, so the rouge breaks down thoroughly, the other that one gets some idea of contact by observing the depth of color of the polishing mixture as the lap moves back and forth.

—223 S St. N. E.

Date	Stroke	Tool	Time	Appearance	Remarks
6-21-'32	1½"	Full	10 hrs		Oblate spheroid with one high zone
6-22-'32	1½"	Full	5 "		Oblate spheroid high rim and center
6-23-'32	2"	Full	5 "		Oblate spheroid high rim and center
7- 2-'32	2"	Full	5 "		Regular oblate spheroid—turned edge
7- 5-'32	2"	Full	3 "		Sphere with 1¼" turned edge
7- 5-'32	4"	Full	3 "		Sphere with central hill and turned edge
7- 6-'32	3"	Full	3 "		Sphere with ⅜" turned edge
7- 7-'32	1¼"	8"	3 "		Turned edge narrower, but new hill
7- 8-'32	2"	8"	3 "		Hyperbola, 1" over-correction
7- 8-'32	1½"	8" ring	3 "		Hyperbola, ¾" over-correction
At this stage the mirror was turned face upward.					
7-12-'32	1¾"	Full	3 hrs		Parabola, but not sufficiently polished
7-12-'32	1¾"	Full	2 "		Did it with honeycomb
7-13-'32	1¾"	Full (pitch)	5 "		ZnO and india ink,OK. parabola with proper correction
			Total 53 hours		

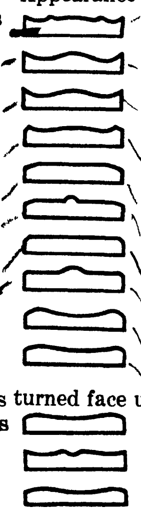


FIGURE 1

Mr. Beardsley's log of the 12" metal mirror job. Noting the long, tedious spells which make up the record, one is reminded of a slow motion picture —a feature of metal jobs.

Astigmatism

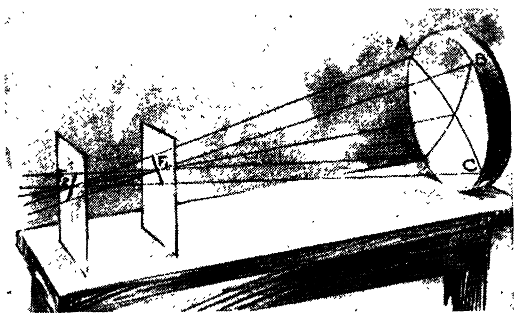
By G. E. Warner
Chicago, Illinois

The term astigmatism is applied to an optical fault which causes images of points not to be points. The word "point" is used in the sense that a dot is a point—not referring to an arrow shape.

Astigmatism is found normally inherent in many types of optical equipment. Most commonly it is present in the off-axis images of telescope objectives, especially reflectors. This chapter, however, deals not with the normal astigmatism, but with that class which is due to abnormalities of the instrument brought about by faulty conditions of making.

To begin with, the astigmatism of a speculum is usually such that the radius of curvature as measured across various diameters is not the same for all. It is very much as if we took a perfectly figured mirror and bent it slightly across one diameter.

In the illustration, Figure 1, the scale is, of course, much exaggerated. The mirror is supposed to be deformed so that across the diameter *AC* its



Drawings by R. W. Porter, after the author

FIGURE 1

radius is at F_2, while across *BD* it is at F_1. With a mirror of this shape it is impossible to get a true point image of a point source. Suppose we examine the shapes of the images which we would see if we used an eyepiece while the mirror was set up à-la-Foucault.

If we are sufficiently far outside of the plane through F_2, our first view of the out-of-focus disk will show it to be quite circular in shape. As we move our ocular toward F_2, however, the disk will become very elliptical as it contracts. When the plane of F_2 is reached the image will be a line of the width of the pinhole of our source, but considerably elongated. The reason for this appearance is evident from the illustration. At F_2 we are in focus for the diameter *AC*, but we are out of focus for the diameter *BD*.

As we progress from this point, moving our eyepiece toward the mirror,

we shall see the image become quite circular, but increasing in its diameter from the minimum previously observed. When the image is most nearly circular, at a point about half way between F_1 and F_2, it is still far from perfect. It is many times the size of a true anastigmatic image. Because of this it can easily be seen how very ruinous astigmatism can be to telescopic definition.

When the ocular is moved toward the mirror, the image again assumes an elliptical form, narrowing in one dimension while it lengthens in the other. This elongation is at 90° from that first seen. The ratio of the length to the breadth of the image again reaches its greatest value when the eyepiece is focused on the plane of F_1.

When the eyepiece is pushed still farther toward the mirror, the image is

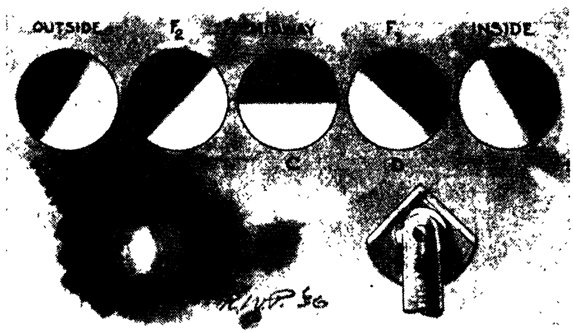


FIGURE 2

again seen to expand, first being very elliptical and gradually losing its eccentricity as it grows.

We can analyze how an astigmatic spherical mirror would look under Foucault test by referring again to the illustration.

Suppose we intersect the light coming from the mirror with a vertical knife-edge. If we insert it from the left at F_1 we can see that it is the light coming from *A* that will first be cut off, hence that part of the mirror will be the first seen to darken. As the knife-edge advances into the cones it will, when it reaches the center of the beam, cut off the rays from *B* and *D*. The ray from *C* will still be uncut. We see, then, that the shadow will first appear at *A* and will have its edge parallel to *BD*, as at *A*, Figure 2. As we cut in, it will advance diagonally across the mirror's face, following the direction of *AC* of Figure 1. The blade is of course vertical, but the shadow appears like the one in Figure 2 at *B*.

Choosing the point midway between F_1 and F_2 in which to insert the knife-edge, we can see that it will be the rays from *A* and *B* that are cut,

while those from *C* and *D* are unscathed. The appearance then will be like Figure 2 at *C*.

When inserted in the plane of F_2 the knife-edge will first encounter the ray from *B*, and then, when the center is reached, it will cut those from *A* and *C*, giving us an appearance like that of Figure 2 at *D*.

If the knife-edge cuts the cone of light much inside of F_1 or outside F_2 the shadow's edge will be more nearly vertical, as in Figure 2 at *E*. The sequence of shadow shapes that we would see, if our knife-edge was mounted on an accurate carriage, alined with the mirror's axis and cut into the cone just half way, would be like those in Figure 2.

This, of course, can cover only the case of a mirror that is spherical except for the astigmatism. Other shapes of surfaces give other appearances. The most common of these is that exhibited by an astigmatic paraboloid, hyperboloid or ellipsoid—the monad.

Again referring to Figure 1, if we should orient either the mirror or the knife-edge so that, when the latter is cut into the cone at F_1 it would be parallel to the focal line at that position, it would then cut all rays coming from the mirror simultaneously and the mirror would be seen to darken evenly all over. With the knife-edge still parallel to F_1 let us cut into the plane of F_2. The ray from *B* is the first cut; then, as the center is reached, the rays from *A* and *C* are intercepted and finally the *D* ray is stopped. The shadow seen is one whose edge is parallel to *AC* and progressing from *B* to *D*, opposite in direction to the cutting of the knife-edge. This is a normal indication, in a perfectly spherical mirror, that the knife-edge is cutting the cone outside the *C* of *C*. Thus, if we should happen to set up even a severly astigmatic mirror and accidentally have either axis of the astigmatism parallel to the knife blade, we would get no indication of this defect from the shadow test.

The infallible test for the presence or absence of astigmatism is one performed with the mirror set up in a perfectly collimated telescope. The stars' images produced by it are examined with as high-powered an ocular as is available. If astigmatism is present, racking the eyepiece slightly in and out of focus will show the tell-tale elongations.

In the shop a tiny pinhole as a source, not too brightly illuminated, and a short-focused eyepiece for examining the image, will suffice to detect most ordinary cases of astigmatism. The ocular must be correctly alined with the mirror, otherwise a confusing effect is sometimes seen. The astigmatic indication as seen in this test—the elongation of the slightly out-of-focus image—must follow a rotation of the mirror, otherwise it is a spurious effect due to the test set-up.

The matter of determining the axes of the astigmatism is quite important to the worker of speculae, inasmuch as any corrective measures to be applied will have to be carefully directed so that the figure be corrected and not further distorted. Also, the discrepancy between the F_1 and F_2 points is of practical importance. There are several possible methods for gaining the desired information.

First, the eyepiece method—noting the two focal points F_1 and F_2 and observing the direction of elongation of the image at either focus. Referring to Figure 1 again, we can see that if we are in focus with the shorter curvature, as at F_1, the elongation of the image will be in line with the long curvature axis. If the separation between F_1 and F_2 is not very great (under 1/16") it is difficult to determine the exact location of these points and the measurement is subject to large errors. Mirrors having several zones, or in which the parabolic corrections are present, offer another difficulty, in that the image seen in the eyepiece is subject to aberration.

The second method, a modification of the first, is one in which a mask is placed over the face of the mirror while it is under test. This mask has two equal apertures, diametrically opposite each other, over the marginal zone of the mirror. With the mask in place the eyepiece can be very accurately re-focused because, when out of focus, the image will appear double, like Figure 2, lower left. Also, if our pinhole is sufficiently small and our eyepiece high enough in power, interference fringes will be seen when the focus is reached.

The focus of our starting position of the mask can be taken as zero and then, rotating the mask about the mirror's center, the focal length checked at each of several orientations and compared with that of the original position. We may tabulate our resulting figures or make a graph to represent them. The graph of a simple flexured mirror will be sinusoidal. After local corrections have been applied it will usually be found that the curve of our graph becomes somewhat irregular. Our graph will then indicate where and the amount of the further correction needed.

A third method, not exceedingly accurate, depends on the fact that the Foucault test fails to show the evidence of astigmatism when the knife-edge parallels one of the axes of the distortion. For this test the writer has used a knife of the form shown in Figure 2, at right. The two upper edges are sharpened, and the angle between them is 90°. The blade can be rotated in a vertical plane about a pivot. In the test the knife-edge is rotated about on the pivot until, when inserted into the average center of curvature, none of the curious distorted figures appear. The knife-edge, without its angle being changed, may then be moved across through the image until the other edge just intersects the beam. If the first edge was inserted at the average c of c of the mirror, the second edge will, if moved at right angles to the beam, appear to be inside or outside of the average c of c. The amount it is necessary to move the second edge to or from the mirror to obtain the same "depth" appearance as the first edge gave, will be the discrepancy between the foci of the two astigmatic axes.

This method, of course, is not accurate because of the difficulty in determining the exact angle and the c of c if the mirror is not spherical.

Of the causes of astigmatism, improper support of the mirror in working "face up"—not in the polishing as much as in the grinding stages—is probably the most prolific source. This is because, in grinding, there is little or no occasion to move the mirror about on its support, so that all the

grinding is done while the mirror is flexed in one direction. While being polished, the mirror is frequently removed from its support for the purpose of testing and, as a result, its position on the polishing pedestal or machine is periodically changed, so that the effects of the various flexures are practically sure to average themselves out.

Working in the conventional manner—mirror on top—there is less likelihood of encountering severe cases, but they can and do show up occasionally. Their principal causes are improper motion during the grinding or polishing stages, usually failure to rotate the mirror in the hands, and the use of too large a handle. A wooden handle will usually warp because of the liquids involved in the operations. The pitch fastening will yield, but not fast

The author.

enough. If work is done while the warping is in progress sufficient stress will be transmitted to the mirror to cause trouble.

Note by John H. Hindle, Witton, Blackburn, Lancs., England: Astigmatism is such an insidious thing that I don't believe one amateur in a hundred knows how to recognize it. Only the greatest care can keep it out. If the mirror is face up during grinding or polishing an improper support will undoubtedly cause astigmatism. I do not bar the use of small polishers, along with that of a full-size, or a nearly full-size polisher to maintain a surface of revolution, and I use small polishers on my drill press polisher for faulty zones, but afterwards use the large polisher to finish with. Much depends upon the definition of a "small" polisher. I should say, one less than half the diameter. But to *entirely* produce a mirror face to the accuracy necessary, and entirely free from astigmatism, by promiscuous *hand* polishing with small polishers, does not seem to me to have any probability about it.

The shadows on the face of an astigmatic mirror are not necessarily of a "monad" form. The orthodox method of recognizing astigmatism on the

sky is by the want of circularity of the extra-focal star images, and in the workshop the same idea is used, with an extremely small pinhole. A very minute pinhole is not indispensable if one knows one's pinhole. I have used the same pinhole for many years and know the minute details of the surface of the ground glass prism forming the "background" of the pinhole, as well as the minute irregularities of the edge. If there is the slightest astigmatism these details are not so well defined with any eyepiece, and there is a curious diagonal or other movement of the *texture* of the pinhole when going beyond focus on either side, even when the expanded images are approximately round. This movement of detail might be compared with that which would be apparent on the surface of a piece of rubber alternately stretched and released under the microscope. It is important there should be *no movement of the detail* when expanding the image. Every little speck should remain in the same position, merely becoming less distinct.

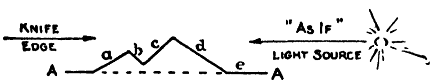
Foucault's Shadows

By E. Gaviola
Director, Observatorio Astronómico, La Plata, Argentina

I: The "As If" Light Source

When testing an optical surface with the help of a knife-edge and a pinhole placed at the center of curvature, or at the focus if a flat is used, the appearance of the dark and bright zones observed is interpreted elementarily by assuming the existence of an imaginary light source situated on one side of the surface, illuminating it grazingly ("A.T.M.," page 11, Figure 14). The aspect of the front face of a mirror disk, for example, is compared with a similarly shaped landscape illuminated by the sun near or at the horizon and viewed by an observer flying over it. This interpretation is simple and very useful indeed, but it offers some difficulties that may justify its modification.

Let us assume that *A-A* (Figure 1) is a spherical mirror surface containing an irregular elevated zone. We place pinhole and knife-edge at the center of curvature and displace the last transversely until it begins to cut the image of the first. The surface element *c* becomes dark first, then *a*, while *b* and *d* are still shining brightly. The elementary interpretation ex-



All drawings by Russell W. Porter, after the author

Figure 1

plains this by saying that *b* and *d* have a positive slope (let us call it so) and are illuminated by the imaginary light source situated at the right of the picture, while *a* and *c* have negative slopes and do not receive any light from it. Now at this stage two shortcomings of the explanation appear to the sophisticated mind. It is not explained why *c* becomes dark before *a*, and why the shadow of the ridge *c-d* does not make the element *b* appear dark too. The zone *b* is illuminated by the imaginary light source, as if the ridge *c-d* were not in the way.

Let us continue displacing the knife-edge. The elements of the "perfect" spherical surface, like *e*, will become dark first. Then *d* will be covered by shadows while *b* is still bright. Where is the imaginary light source now? The elementary explanation would have to answer: "Nowhere—the 'as if' grazing illumination assumption should be applied only until the knife-edge is half way through the image." But there is the additional difficulty mentioned already, that *c* becomes dark before *a* does. If we put the elementary explanation against the wall, it will defend itself thus: "The interpretation of the zones of light and of shadows by the presence of an imaginary light source illuminating the mirror surface grazingly, is subject (1) to the assumption that each surface element appears independently of all

the others, as if the rest of the mirror did not exist, and (2) to the experimental requirement that the knife-edge shall be exactly half way through the image of the pinhole."

The sophisticated mind can answer: "So far, so good, but how can we know *when* the knife-edge is covering exactly half of the image? This would be easy enough if the mirror contained elements of the 'perfect' sphere, like *e* in Figure 1, and if we knew where they were. But actual mirrors are not so obliging as to tell us so much."

Let us now stop arguing and try to construct, after destroying. The interpretation of the shadows can be expanded so as to meet some of the shortcomings which have been noted. This is done by imagining that the "as if" light source, instead of staying put at 6 o'clock (Figure 2), rotates

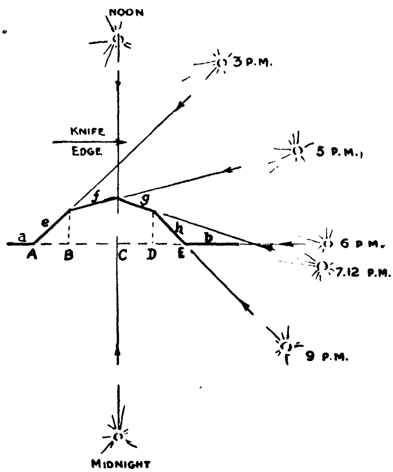


FIGURE 2

around the mirror as the knife-edge progresses through the image of the pinhole on its transverse motion. Before and until the knife-edge begins to cut the image, we can assume that the imaginary light source is at the *noon* position, directly in front and at a fair distance from the face of the mirror. The whole surface therefore appears illuminated. As the knife-edge starts intersecting the image, the "sun" moves from the zenith toward the horizon. At 3 P.M. the surface element *e* darkens (Figure 2), while the rest remains bright. A further displacement of the knife-edge will correspond to a further rotation of the sun. When it reaches 5 P.M., it begins darkening the surface element *f*. When the knife-edge is half way through the image, the corresponding position of the sun is at the horizon, and *a* and *b* will darken.

At this moment we have the conditions of the elementary interpretation. If we proceed, displacing the knife-edge in the same direction, the element *g*

will fade out next. To explain this we can assume that the sun is now below the horizon, at the 7:12 P.M. position. For this, however, we have to adopt the terms of the elementary assumption: "Each surface element appears independently of all others, as if the rest of the mirror did not exist." Then it becomes possible for the sun below the horizon still to shine on the hill slopes looking toward the west. When the knife-edge reaches the position connected with 9 P.M. the last bright element *h* is overtaken by shadows. A further displacement of the knife-edge will not produce any alterations. We can assume, then, that the sun is stationary at its midnight position of rest. On retreating the knife-edge to its original position, the sun will reverse its course, rising in the west.

If the conception of the sun shining on the westward-looking hill slopes after sunset is unpalatable, we may substitute for it another one which, I am afraid, will be palatable to only a few readers. At the moment when the bright sun sets in the west we may imagine a black sun rising in the east. This black sun, instead of throwing light, will radiate shadows. The surface is naturally bright, unless reached by the dark rays. At 6 A.M. the elements *e* and *f* will be covered by the shadows of the black sun; at 7:12 A.M. the light on *g* will be swept away by the dark rays, and so on.

We still have to answer the question about where the crest of the raised zone is. It is at the limit between light and shadows, when the sun is setting at the horizon. But how can we tell the 6 P.M. position? To answer this we have to go a step further and introduce a scale which will measure the lateral displacements of the knife-edge. If we take readings on this scale, corresponding to the darkening of all and every element on the surface of the mirror, the mean value of the readings is the 6 P.M. position of the knife-edge. The question is thus answered.

But these readings tell us much more than where the crest of the zone is. We can deduce from them the shape of the raised zone and of the whole surface of the mirror in a quantitative way. We can tell not only where the crest is, but also how high it is above the surface of reference. But this leads us into a new field, which requires a different approach.

II: A Differential Survey of an Optical Surface

It is well known that a paraboloid can be recognized, when testing at the center of curvature, by measuring the focal length of circular zones. The same is true for any figure having central symmetry. The last is a necessary condition. As soon as we meet a non-central-symmetrical surface the survey by circular zones fails. The mirror maker generally takes special care to keep his figure in a condition of circular symmetry, but he does not always succeed. He then has no method of knowing quantitatively the shape of his figure. And that knowledge would be useful in correcting afterward the non-symmetric irregularities. The zonal method of surveying fails completely—in the case of an off-axis paraboloid, for example. The same is true for all figures whose center of symmetry does not lie at the center of the glass disk.

The fundamental reason for the limited applicability of the zonal survey is that it is an "integral" method. It measures focal lengths. Now it is extremely difficult to determine experimentally the focal distance of an isolated small surface element. The measurement of focal lengths requires the use of at least two surface elements at not too small a distance from each other. Measuring a focal length with the knife-edge and pinhole requires, further, that the two elements be on the same diameter and at equal distances from the optical center.

All this made desirable the development of a "differential" method of surveying optical surfaces. This method had to be applicable to surveys of local irregularities, as well as to non-symmetric and to symmetric surfaces.

Description of Method: Let us consider a spherical mirror possessing an asymmetric circular zone *a-b*, *c-d* (Figure 3). Let *O* be the center of curvature, *L* the pinhole light source and *I* its image formed by the spherical part of the mirror. Let us start the observation with the knife-edge in such a

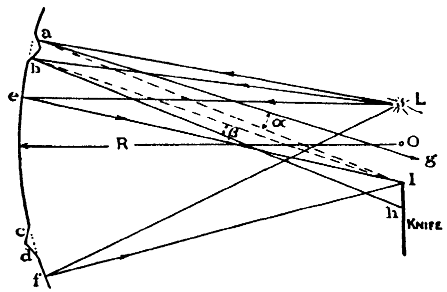


FIGURE 3

position that it does not yet intercept any light reflected by the mirror. When the edge of the knife is displaced until it reaches the position *h*, the zone *b* will darken upon the mirror's face. A further displacement up to *I* will make the spherical part of the mirror fade out. Now this distance *hI* can be measured by a suitable arrangement. Dividing it by the radius of curvature *R*, we obtain the magnitude of the angle β between the actual reflected ray *bh* and the ray *bI* that would be reflected by the theoretical surface.* This angle β is equal to twice the inclination of the element *b* with regard to the perfect sphere of reference. If we call z the distance which the knife-edge has to be displaced from its mean position at *I*, in order to make a given surface-element change from light to darkness or vice versa, then $z/2R$ is equal to the inclination of that element with regard to the surface of reference. We have assumed so far that the light source *L* is not

* For numerical apertures smaller than $f/4$ it is necessary to multiply the displacement by the cosine of the angle of the light beam with the optical axis.

displaced together with the knife-edge. If it is, then z/R has to be used instead.

Let us go back to Figure 3. A further displacement of the knife, until the edge intercepts the ray *a-g*, allows us to determine the magnitude of the angle α and of the steepness of the zonal element *a*. We can, moreover, read the width of the zones *a* and *b* directly with the naked eye, or with a small telescope placed behind the knife-edge, if we put a suitable scale in contact

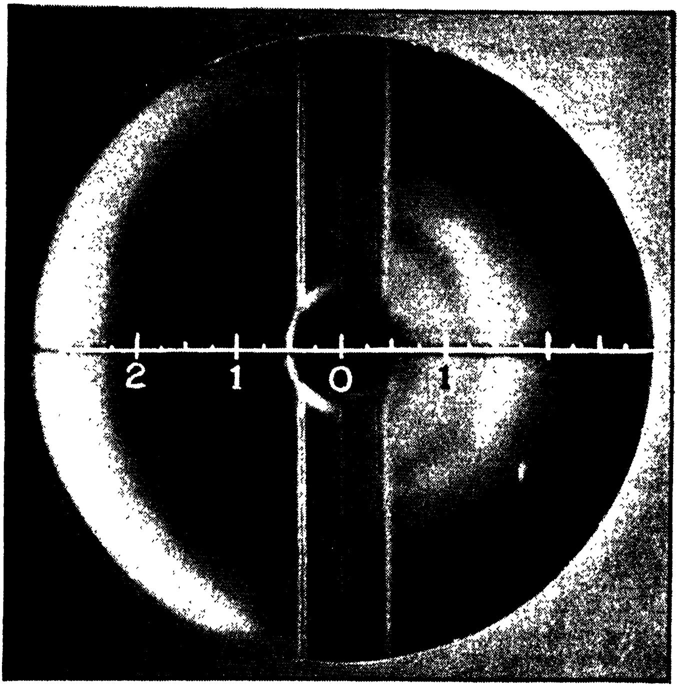


FIGURE 4

with the surface of the mirror. Now, knowing the steepness and the width of the zones *a* and *b*, we can calculate the altitude of the ridge *ab* and, moreover, reconstruct quantitatively the whole elevated zone. We can survey the zone *c-d* in an analogous way.

In the foregoing description we have assumed that we know where the image *I* is. This is not so in a practical case. The theoretical place of the image can be defined as the mean value of the positions of the knife-edge when a sufficiently large number of readings, uniformly distributed, has been

taken across a diameter of the mirror. But this leads us to the need of considering a more general case in some detail.

Parabolic Mirror surveyed at its Center of Curvature: Let Figure 4 be the focogram of a 6″ parabolic mirror of aperture $f/8$, observed with the knife-edge at its center of curvature. We want to determine its figure quantitatively. For this we place a scale across the mirror, near the diameter that is parallel to the direction of displacement of the knife-edge. We fit the knife-edge with a good slow motion screw and a drum in which we can read at least thousandths of an inch and preferably ten thousandths. As the measurements are relative to each other, the screw does not need to be specially calibrated. Any good commercial screw will do. The drum should have a diameter of from 3″ to 5″. Once a certain focal length has been arbitrarily chosen, we can start the survey.

We displace the knife (from left to right in the case of Figure 4) until the first line of shadows appears on the mirror. We read the position of the boundary between light and darkness on the mirror scale, and the corresponding position of the knife-edge on its drum. A further displacement of the knife will make the zone of shadows that appeared first at the extreme left expand toward the right. We take readings at about every quarter inch on the mirror surface. If the focal length chosen is the mean value between the centers of curvature of the central and of the outer zones, when the limit of the shadow reaches the reading 2½″ to the left (to be exact, 0.816 r) a new dark line will appear at 1¼″ on the right (exactly at $r/\sqrt{6}$). From this moment on, and until the bright zone at the left disappears, for each reading of the knife-edge drum we can make three readings of shadow-light boundaries. Beyond this position only one limit remains (provided the mirror has no irregular zones) and we follow it quantitatively until it moves off the mirror disk. The displacement of the knife-edge between the two extreme readings amounts to nearly 3 thousandths of an inch in our particular case.

The "field-work" is now finished and we can proceed to the calculation of our results. We begin by plotting the measured steepness curve in a diagram. We use the vertical axis at the right (Figure 5) for the drum readings and the horizontal axis for the corresponding positions on the mirror surface. If our mirror and our measurements are perfect, we shall obtain the steepness curve of Figure 5. Otherwise we shall approximate it more or less. In the scale at the left of the diagram the values of the numerical steepness $(= z/2R)$ are indicated. In a practical case it is better to plot the directly measured displacements z.

Now that we have our steepness curve we can determine the position of the theoretical image (I in Figure 3). This position is the zero line of the steepness diagram. Up to now it has been hanging in the air. We have to give it a base line of reference. Such a base line is A-A in Figure 5. It has been chosen parallel to the horizontal axis and at such a level that the

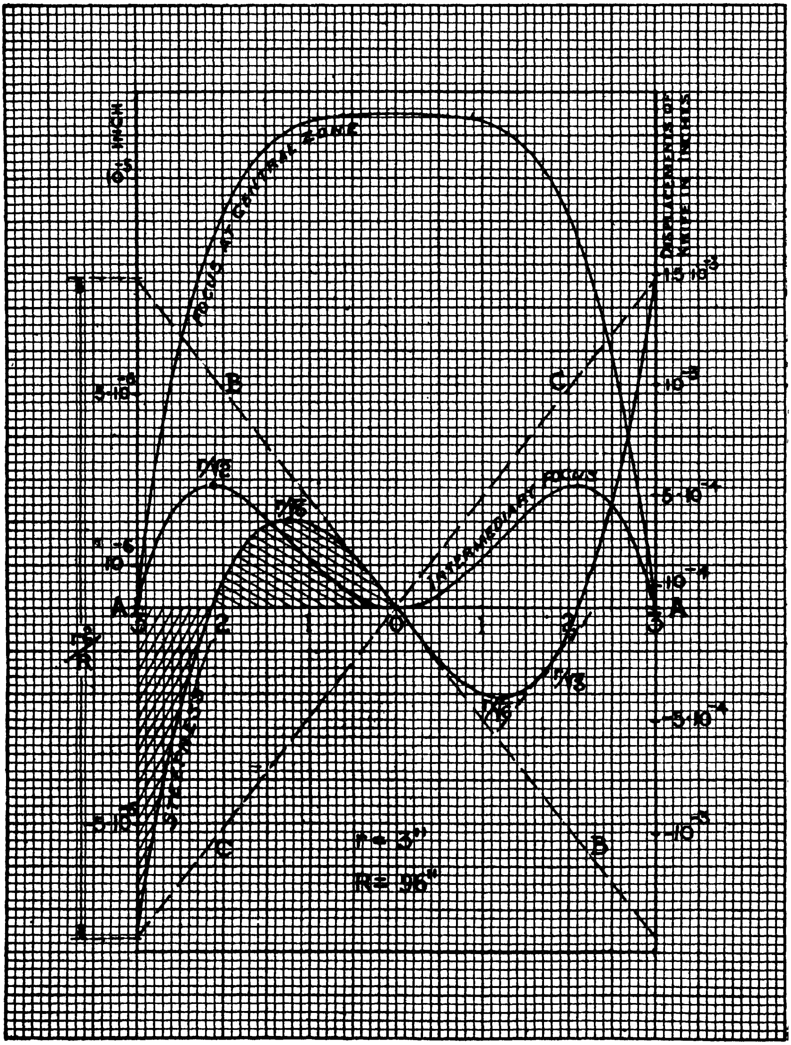

FOCUS AT CENTRAL ZONE
INTERMEDIARY FOCUS
DISPLACEMENTS OF KNIFE IN INCHES
10^{-5} INCH
15·10^{-3}
10^{-3}
5·10^{-4}
10^{-4}
-5·10^{-4}
-10^{-3}
5·10^{-6}
10^{-6}
-5·10^{-6}
A
B
C
0
1
2
3
r = 3"
R = 96"

FIGURE 5

surfaces enclosed by it and the steepness curve (shaded) are equal on both sides of it.

The next and final step is now to calculate the contour curve. This is done in exactly the same way in which, from the focal distances of the circular zones, the shape of the mirror is determined, when using the zonal method. The steepness diagram is divided into narrow vertical strips. The strips can be conveniently taken one or more squares of the graph paper in width. We read the mean height of the first strip at the right hand scale (expressed directly in inches of knife-edge displacement), divide it by $2R$ and multiply it by the width of the strip. The result gives us, in inches, the height of the mirror surface above the surface of reference at one strip width from the edge.

We repeat the same operation with the second strip and *add* the result to the previous one. As will be seen, the mean height of the strip, times its width, is simply the area of the strip. This area is a measure of how much higher the mirror surface is at the left than at the right limit of the strip. (We are assuming that we begin the calculation at the right end). When the steepness curve crosses to the other side of the zero line *A-A* we have to subtract from, instead of adding to the previous height. The end result is the "intermediary focus" curve of Figure 5. (The left hand scale, read in inches, should be used for this and for the central zone curve.) This is the well known apparent shape of a parabolic mirror. There is an intimate relation between the contour curve and the steepness diagram. Where the last is zero (for *0* and for $r\sqrt{2}$) the first has either a maximum or a minimum. To the greatest values of the steepness line, at $r\sqrt{6}$ and at the periphery, correspond the most inclined slopes of the figure; and so on.

Change in Focal Length and the Behavior of Shadows: If we want to know how the mirror looks when the central zone is in focus, we need not measure a new steepness curve at a new position of the knife-edge. The old one will do. We need only to rotate the zero line *A-A* around the point *0* until it reaches the position *B-B*, and use this last as a base line of reference for a new graphical calculation. The line *B-B* is determined by two characteristics: it is tangent to the steepness diagram at *0* and it intersects the vertical axis at the left at a distance from *A* equal to the distance from this point to the lower end of the steepness curve.

Let us now divide the surface between the new zero line and the steepness curve into vertical strips, read the mean height of each, multiply by its width, divide by $2R$, and plot a new contour curve. The result is the apparent shape of a parabolic mirror when the central zone is in focus. It is worth noticing (Figure 5) that the elevation of the central part of this curve is exactly four times higher than the greatest altitude reached by the contour observed at the intermediary focus.

If we want to know how the mirror looks when the very edge is in focus, we take the base *C-C* as zero line and repeat the previous procedure. The result is not indicated in Figure 5. I leave this case, and all the others corresponding to intermediary positions of the zero line between *B-B* and

C-C, to the interested reader, as a practical exercise. He will discover that this is a job that is easier to do than to describe. The focal length to which any zero line corresponds can be read directly on the vertical axis. From B-B to C-C we have increased the focal length by r^2/R (provided the pinhole is not displaced together with the knife-edge, otherwise $r^2/2R$). A-A lying halfway between, corresponds to the mean focus. In general, the displacement of the focus is proportional to the segments of vertical axis intercepted by the zero line.

The diagram makes apparent that it is difficult to determine experimentally the focal length of zones near the periphery of the mirror, because the focus changes there rapidly with the position and with the width of the zone: The zero line cannot be made parallel to any such zone. And this is a necessary condition for an accurate measurement of focal length. This condition is fulfilled by using the lines A-A and B-B. The first is parallel to the zone $r/\sqrt{6}$ and the second to a fairly wide central zone.

There is still one more set of facts which can be read out of Figure 5. As we know already, the inclination of the zero line indicates the chosen focal length. Furthermore, a parallel displacement of it, keeping the inclination constant, corresponds to the transversal displacement of the knife-edge at a given focal length. At 12 noon the zero line is at the bottom of the diagram and does not yet intercept the steepness curve anywhere. If we move the zero line upward, parallel to itself, the point at which it first touches the steepness curve indicates where the first line of shadows will appear on the surface of the mirror. Displacing it farther, the point of intersection will move along it. This corresponds to the expanding of the shadows. If we are using a zero line parallel to A-A we can observe that, when we have displaced the knife-edge 1.07 thousandths of an inch from the point at which the first line of shadows appeared at the periphery, a new dark zone will start at $r/\sqrt{6}$ and will grow in both directions. Furthermore, we can notice that the focogram of Figure 4 was taken when the knife-edge had not yet reached its mean position. In fact, the boundaries of shadows lie at 2¼″ on the left and at 2″ on the right. This corresponds to a position of the zero line A-A displaced 0.134×10^{-3}″ in the negative direction (Figure 5), which is the distance that the knife-edge still has to be displaced in order to halve the image.

This observation furnishes an idea about the accuracy of the method. We see that the effect of a displacement of a 10,000″ in the knife-edge is clearly noticeable, and measurable in the positions on the shadows. It makes another thing plain: That the whole survey can be done by taking a succession of focograms corresponding to regular small displacements of the knife-edge (at a constant focal length). The focograms should be taken on the same film roll and the film should be developed uniformly, in order to assure equal contrast for all of the pictures. I consider this the most accurate way of surveying. But the visual survey can easily be carried to

an accuracy of one twentieth of a wave-length, which is amply sufficient in most cases.

Technicalities: The magnitude of the knife-edge displacements to be measured, as has been mentioned already, is of the order of a thousandth of an inch. These displacements ought to be measured within an error of no more than a few ten thousandths. This requires the observance of some precautions during measurement. Mirror and knife-edge plus light source

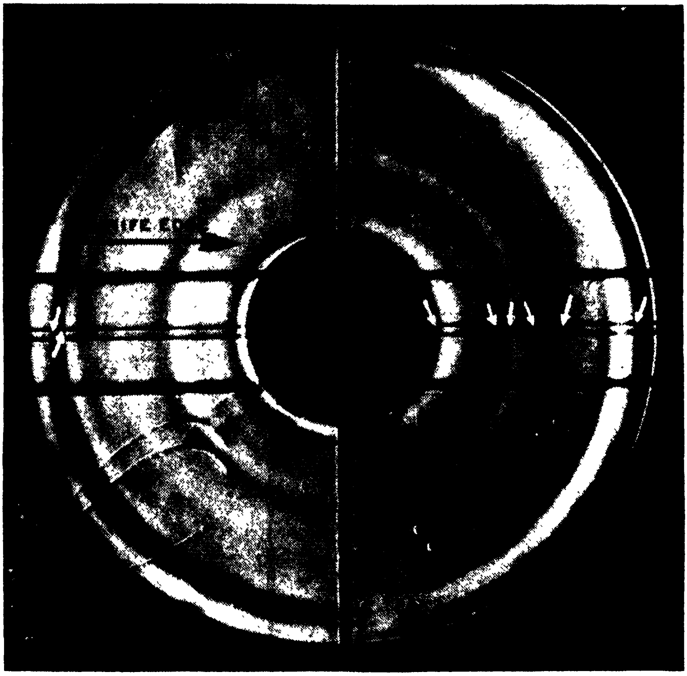


FIGURE 6

have to rest on solid supports as free from distortions produced by changes in temperature and in humidity as possible. Even then, slow irregular variations of the relative position of the knife-edge with regard to the mirror will be observed. These wanderings of the system would introduce serious systematic errors, but it is possible to compensate for them because they are slow. If the whole measurement along one diameter of a mirror is done in, say, less than one minute, then one may safely assume that the deformation of the system during that time is practically uniform. The repetition of the two first readings at the end of a series will then disclose the value of

the deformation. This can be equally divided among the intermediary readings, thus eliminating the error.

In the case of a regular surface the number of shadow-light boundaries is small, usually one or three. Their positions can then be rapidly read on the scale which is in contact with the surface of the mirror. But if several circular zones are present the number of limits to be observed grows considerably. In the case reproduced in Figure 6 there are eight boundaries between light and shadows (indicated by arrows) for the particular position the knife-edge had during the exposure. A further small displacement of the knife would add eight more to this number. Now, if one attempts to read the positions of these eight or even 16 limits without touching the knife-edge, one would discover that it is, in most cases, impossible. During the time required for arriving at the last readings the aspect of the first zones has changed thoroughly. The thing to do is to *prepare* the readings before making them. A measuring plan is prepared by writing down where the first dark edge or zone appears when the knife is caused slowly to intersect the image. Then those points along the diameter of the mirror, parallel to the scale, are noted that fade out simultaneously for successive positions of the knife-edge. During this operation each position of the knife-edge has to be *kept* dynamically constant by compensating changes in the light-shadow system with small displacements of the knife-edge drum. After the measuring plan is completed, then the positions of the knife-edge for each set of limits are read on the graduated drum. The sets of limits should be taken close enough to avoid ambiguities in the drawing of the steepness curve. One must keep in mind that a local error in this curve produces a systematic one in the contour curve.

The careful preparation of the measuring plan has two purposes: First, it simplifies the task of making readings, as each drum reading corresponds in general to several points on the mirror; second, it avoids the systematic errors due to wanderings of the knife-edge, because it shortens the time of measurement.

When using the focogram method of surveying, at the end of a series of pictures the first or second one should be repeated, for control and correction of errors.—*On board the* S.S. Hardanger, *November 24, 1935. 6° S. Lat. and West of Peru.*

[EDITOR'S NOTE: A parallel though a little more technical discussion of the ground covered by this chapter, written by the same author, may be found in the *Journal of the Optical Society of America,* April, 1936, pages 163–169.]

The Zernike Test

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I: On the Use of Small Stars

(in the knife-edge test, and for the Zernike test)

What size star ought we to use for the knife-edge test? Contradictory opinions have been published. Ellison ("A.T.M.," p. 84) "has known grotesque errors result from using too fine a hole." The user who did this "saw a series of diffraction bands inside the margin of his mirror, and took them for a turned-down edge." G. W. Ritchey, on the other hand, writes (quoted from "A.T.M.," p. 294): "When the knife-edge test is used with an extremely small pinhole between $\frac{1}{250}$th and $\frac{1}{500}$th of an inch in diameter, illuminated by acetylene, or what is much better, oxy-acetylene or electric arc light, minute zonal irregularities are strongly and brilliantly shown, which are entirely invisible with large pinhole or insufficient illumination." What in fact determines the delicacy of the knife-edge test?

If light traveled in straight lines, a given zone would show quite black on a fully bright mirror (or conversely) if its tilt with respect to true figure was just enough to divert the rays reaching it from every part of the pinhole, so that they fell completely clear of the image of the pinhole formed by the rest of the mirror. The delicacy of the test would then be inversely proportional to the diameter of the pinhole (provided enough light could be got through the pinhole). If on the other hand we ask, not that a given zone should show fully bright, but merely that it should show *appreciably* bright on a fully black mirror, the delicacy of the test will be limited only by the intrinsic brilliance of the source feeding the pinhole. On the "ray" theory of light, then, we should make the source as bright as possible, and the pinhole only just large enough to let through a reasonable amount of light.

But, as we hope to test correct to a small fraction of a wave-length, we must take into account the wave properties of light. We can then argue that since the mirror cannot produce a "point" image of a "point" pinhole, but produces an "Airy disk" of finite width, we shall not gain much in delicacy by reducing the diameter of the pinhole below that of the Airy disk produced by the mirror—which depends on the focal ratio at which the mirror receives the light from the pinhole.

Thus, for testing a spherical mirror of diameter D, radius of curvature $R = 2F$, we should use a pinhole of the order of smallness of $0.001 \frac{F}{D}$ mms. diameter. So, for example, a spherical mirror of $D = 6''$, $R = 8'$, should be tested with a pinhole not bigger than 0.008 mm. = 0.00032″ diameter—a hole six times smaller than the smallest hole advised even by Ritchey.

This raises immediately the question of whether one will see a series of diffraction rings round the edge of the mirror—for if such rings are seen, much of the advantage of the small pinhole would presumably be lost. You

cannot do good optics by guessing what things would look like if they were not surrounded by diffraction rings.

When I first used the knife-edge test, I used a hole 0.013 mm. diameter, and saw about six diffraction rings inside the edge of the mirror (no knife-edge being present). It was difficult to know what to do about these rings, and in desperation I decided to work out theoretically how they should behave. My result was that they should be invisible, because their spacing on the retina should only just equal the resolving power of the eye-lens, and the retina would then be incapable of resolving them. I looked at the mirror again, and was able to count six distinct rings. I then remembered that Lord Rayleigh had made a similar calculation many years ago. On referring to it, I found that he also concluded (in effect) that no rings should be visible. I looked at the mirror for the third time, and could not see any diffraction rings. . . !

It was all very mysterious: I could understand the mirror showing its contempt for my theoretical treatment, but it must have known that Lord Rayleigh had made the same calculation before. A year later, I found the explanation: a visitor, looking at the mirror, complained of diffraction rings, which I could not see, and it occurred to me to look at it through his spectacles, which he had taken off. I then saw the rings, and when he wore his spectacles he saw no rings.

Theory predicts that, if you focus your eye not on the mirror but in front of it or behind it, you will see diffraction rings around its edge. (The extreme example of this is the series of rings seen in the extra-focal image of the star, which is after all, also the extra-focal image of the mirror!)

The reason why anyone with normal sight tends to focus his eye anywhere but on the surface of the mirror is simply that, if for a brief moment he malfocuses the mirror, he sees diffraction rings, and his eye automatically tries a further change of focus in the direction that enabled it to see something—the rings—which it had not seen before. Therefore the proper advice to give to such an one, who complains of diffraction rings, may be cast in the epigrammatic (if exasperating) form, "If you don't look at them, you won't see them!" If he still sees them, there is nothing for it but the right spectacles, and—in the last resort—a friendly oculist to paralyze the focusing muscles of his eye with the appropriate "dope," so that he cannot unconsciously vary his focus. But it is worth while, before adopting so drastic a measure, first simply to use the test for some hours. Refraining from malfocusing one's eye is like riding a bicycle—most of us have to learn it by practice, but when learnt, it is quite automatic.

There remains the question of how to get enough light through a hole as small as 0.008 mm. diameter. It is necessary to use a source of very high intrinsic brilliance, such as a gas-filled lamp, or a Pointolite, or an arc, and since these sources are too small to provide the required solid angle of light even when placed as close to the hole as is practicable, it is necessary to use a condensing lens, to form an image of the source on the hole. One need not, however, correct the aberrations of the condensing lens completely, or

even at all. These aberrations will cause the image of the *hole* which the lens forms on the source to be larger than it would otherwise be, but provided this image is not larger than the source, the aberrations will not reduce the light issuing from the hole, nor will they falsify the test by appearing on the mirror. I use a 12-volt, 16-watt gas-filled lamp, the filament of which is coiled in a very close helix, and a simple biconvex lens of 1″ focal length to image it (with unit magnification) via a prism on to the pinhole. To adjust this star, one puts one's eye very close to the pinhole, and moves the lamp (the base of which is fixed on three "leveling" screws) until the blurred patch of light seen through the pinhole is as wide and as bright as possible. The resulting cone of light is wide enough for testing a system imaging at $F/8$: if a wider cone is needed, either the lens must be corrected, or a wider source must be used. As the lateral aberrations of a lens are proportional to its focal length (for given aperture), the focal length of the lens should be as short as the size of the lamp-bulb permits.

One can sometimes find natural holes of the order of 0.01 mm. diameter in 'tinfoil': the following account of the technique of *making* even smaller holes is quoted from the *Monthly Notices* of the R. A. S., March 1936 (p. 452).

"The principal difficulty I found in making pinholes .0025 mm. diameter, by piercing tinfoil with a needle, lay in making the needle really sharp. But Dr. J. M. Dodds, of the Metropolitan-Vickers Co., solved this difficulty by the following honing technique. The needle, mounted on a rod, is first honed on a fine stone until the diameter of its 'point' does not exceed 0.01 mm. This is not difficult, provided one inspects the point frequently during honing with a microscope. The final honing is done on glass. Lay the needle on a glass plate, and press heavily with one finger behind its point. Lift the rod in which it is mounted slightly so that the needle is bent through several degrees. Then, still pressing with the finger, simultaneously twist and withdraw the slightly lifted rod, so drawing out the needle under the pressing finger. This process is repeated until on inspection under 500 diameters magnification the needle looks quite 'sharp'—that is, its 'point' is of the order of 0.001 mm. diameter or even less. Fifteen minutes honing on glass usually suffices.

"The 'tinfoil' in which cigarettes are wrapped forms an excellent material for the pinhole. The foil is tacked (at its edges only) to a glass plate; the needle-point is then placed very gently on it, and the needle rotated without pressure through at least one revolution and then lifted off. Some practice is necessary to avoid dragging the point sideways in lifting it off. If the needle is not rotated the hole will not be reasonably circular. The needle requires rehoning after a few piercings. Not every pierce is successful, but one can in this way make reasonably circular pinholes 0.002 mm. diameter, and occasionally even smaller."

There are two main points of difference in the behavior of the knife-edge test when it is carried out not with a large pinhole, but with a star smaller than the resolving power of the mirror (say, 0.001 F/D mm. dia. for a

sphere tested at its center: 0.0005 F/D mm. for a paraboloid tested at its focus, with a flat).

First, the test becomes noticeably more delicate, especially for slow errors of curvature—simple spherical aberration, and more particularly coma and astigmatism. For example, one obtains appreciable "paraboloid" shadows on a 12″ paraboloid of $F/18$. The test becomes more sensitive without diaphragms than when diaphragms are used, but zonal focal measurements taken without diaphragms can give hopelessly wrong results—as was predicted by Lord Rayleigh, many years ago. A simple (though admittedly loose) way of explaining this is to say that when the knife-edge is not at focus, its shadow is preceded by diffraction fringes (not to be confused with eye-malfocus diffraction rings seen in the absence of the knife-edge). Thus a large error, on one part of the mirror, by putting the knife-edge out of focus for that part, can produce diffraction fringes on an error-free part of the surface. Accordingly, the only part of the error which one can be certain of interpreting correctly is the *largest* error present. This diffraction fringe difficulty automatically decreases as the errors are reduced and vanishes when the mirror is error-free. The mirror then shadows symmetrically as the knife-edge is advanced, but not uniformly, the center darkening before the edges. If the test were interpreted on a "ray" basis one would then say that, since the edges shadow last, one edge must be turned up, and the other turned down—in fact, that the mirror is comatic. One can, however, check whether coma is really present, for if it is, on bringing in the knife-edge in the opposite direction, the edges will shadow before the center.

The second point is that the delicacy of the test—expressed in wave-lengths—becomes independent of the focal ratio of the mirror, provided that the test is made null-fashion, without diaphragms. When diaphragms must be used—as in testing a wide aperture paraboloid at its center of curvature—the limit of observational accuracy always corresponds to an uncertainty of the tilt of each zone amounting to a given fraction of a wave-length at the edge of the zone. It is extremely difficult to reduce this error to one hundredth of a wave-length per zone. Now, the effect of such an error is cumulative: if one zone is measured wrongly by $\lambda/100$ the resulting height calculated for the 10th zone from it, will be in error by $\lambda/10$—a by no means negligible amount. That is why it is preferable to test wide aperture paraboloids, for which many zones would be necessary, at the focus, with the aid of a flat.

Diffraction effects can complicate the "paraboloidal shadows" seen at the center of curvature so much that even at the modest aperture of $F/8$ there may sometimes be difficulty in locating irregular error from the "general run" of the shadows. It may then be preferable to gain ease of interpretation at the expense of sensitivity by increasing the diameter of the pinhole "till it is as big as a porthole" and obvious diffraction troubles disappear. We have to fall back on "ray" theory to determine a reasonable size for the "porthole." On this basis, if we wish to see the "paraboloidal shadows"

ranging in contrast from fully black to fully bright, we should make the "porthole" diameter equal to that of the geometrical circle of least confusion produced by the mirror. That is, for a paraboloid of diameter D, focal length F, we should use a "porthole" of diameter $\frac{D}{64}\left(\frac{D}{F}\right)^2$. So, for example, a 12″ paraboloid of $F/8$ would require a "porthole" 0.003″ diameter.

But to detect a given error we should then have to look for differences of contrast considerably smaller than those with which the same error would show in a spherical mirror tested at its center with a really small star: this is especially the case with the three errors of longest period: coma; astigmatism; and "error" of absolute focal position.

II: On the Zernike Test

The test devised by Professor F. Zernike, and called by him the "method of phase-contrast," enables one to see directly errors of height in a mirror's surface, without having to deduce them from observed errors of tilt. Thus, whereas with the knife-edge test, one deduces that a certain area is high, because one sees that the area to the left of it is tilted to the left, and the area to the right of it is tilted to the right, one sees, with the Zernike test that that area is high, because it is colored blue, whereas other parts of the mirror are colored yellow. Or, it may be, pink and green respectively.

The test is, in fact, a kind of interference test: it shows colors on the mirror very similar to the colored Newton fringes which would be seen if a test plate were placed almost in contact with the mirror's surface.

The test is applied to a spherical mirror * as follows: An artificial star is placed close to the center of curvature, and one's eye is placed just behind the image, as in the knife-edge test. But instead of bringing a knife-edge across the image, one centers upon the image, by means of a micrometer focusing carriage a "Zernike disk"; that is, a circular disk of transparent material, which must be small enough to cover only the central maximum of the Airy disk formed at the image of the star, and thin enough to retard the light passing through it either by ¼ wave-length for all colors, or by a *small* whole number of wave-lengths plus a quarter for some colors, and three-quarters for others.

Z-disks thus have to be of the order of 0.01 mm. diameter, and only a few wave-lengths thick.

The Star: I have described in the preceding chapter how to make the star. The pinhole diameter there suggested, 0.001 F/D mm., is small enough. 0.004 F/D mm. is certainly too big.

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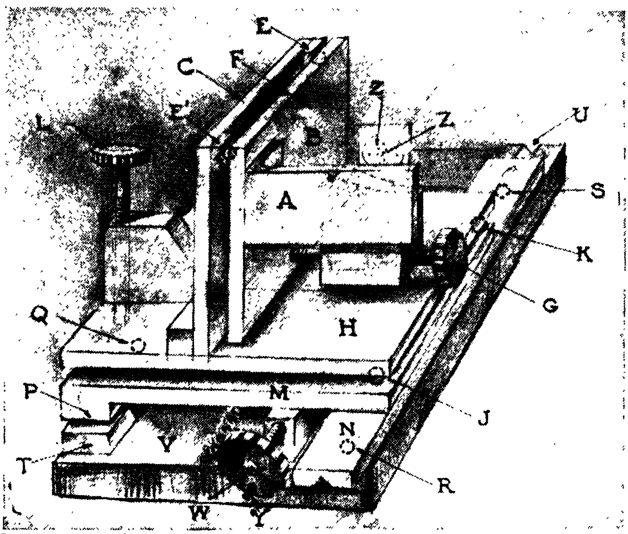
* The Zernike test (pronounced approximately Zer-nicka but shortened to "Z-test") may also be used on paraboloids, null-fashion, that is, without shadow and with even cut-off, as in the Ritchey auto-collimative test made at the focus with a flat. Or it can be made at the c. of c. and without a flat, by means of reflection compensators—auxiliary mirrors described by the author of the present chapter in *M.N.*, R.A.S., March 1936, pages 438–461, a rather mathematical article. For other references on the Zernike test see Zernike, in *M.N.* 1934, p. 377 and in *Physica*, I, No. 8, p. 689. Also Burch, in *M.N.*, 94, p. 384, 1934; Burch and Beeching, in *The Observatory*, 58 (1935).—*Ed.*

The Focusing Carriage: The centering of the Z-disk on the image must be correct to a small fraction of its diameter, and it is practically essential that the centering should not vary as the disk is taken through focus. This is achieved by mounting the Z-disks on a focusing carriage shown in isometric projection in Figure 1.

The Z-disks, *Z, Z,* are mounted on a microscope slide clipped to the bracket *A,* projecting from the vertical plate *B.* This plate is hinged at its



Drawing by Russell W. Porter, after the author

FIGURE 1

The focusing carriage for the Z-test. The base-plate is about 5" wide. The pinhole is not shown, but should be placed at the right of the Z-disk selected, and on a level with it. The author states that with his own carriage he can reduce δ, the half-width of the lateral separation (see text), to 2 mm. This requires a prism, much as in "A.T.M." page 16. The longitudinal separation matters less, as in the Foucault test. "I find it possible to use either eye," he states. "I tilt my head forward and look over the top of imaginary spectacles at the mirror." If the user is left-eyed, the whole carriage should be reversed—like a mirror image—putting the pinhole on the left.

top to the vertical plate *C,* by a "geometrical hinge" consisting of two steel balls, *E', E,* each in a conical depression in *B; E'* bearing on a slot in *C,* pointing toward a conical depression in *C,* in which *E* lies. A strong spring *F,* on the line of centers of *E'* and *E,* keeps the hinge together. By turning the micrometer screw *G,* which is attached (behind and below the Z-slide) to the plate *B,* one causes *B* to rotate about the hinge, and so moves the *Z*-disks approximately vertically (actually, in a circular arc passing through

E'). The plate C is fixed to the horizontal plate H, which is hinged geometrically at J, K, to the plate M. (The hinge spring is not shown). The micrometer screw L attached to C controls the horizontal position of the Z-disks by rotating C about the hinge J, K. The plate M carries on its under side a grooved member N, and a flat member P. The latter rests on the steel ball Q which lies on the flat member T, and the former on two balls, R, S, which lie in the grooved member U. On the base-plate V there is mounted a micrometer screw W, which bears on a block (not shown) fixed to the under side of M.

Two springs, one on each side of W (one not shown) stretch from the middle of the underneath of M to the front of the base V: these springs keep the block underneath M in contact with the focussing screw W. This screw is graduated in 0.001″ divisions: a fiducial line on a simple jig (not shown) can be held in position against V, so that the focal setting can be read to 0.001″, and estimated to 0.0001″. On the front of the dial on this screw, there is a small knob Y, so that when testing in total darkness one can try the effect of changing the focal setting of the Z-disk by an approximately known amount (say, ⅛ turn = 0.003″). This is useful in the preliminary examination of a mirror. On the other hand, when making zonal measurements one can turn the dial of W by its edge, without touching the knob Y, so as to keep oneself in complete ignorance of the numerical value of a setting while one makes it. The fact that, when this precaution is taken, one can often repeat zonal Zernike settings on an $F/6$ mirror (imaging at $F/12$) to ± 0.001″, and knife-edge settings (with diaphragms, to ± about 0.003″, is sufficient justification for graduating the screw in 0.001″ divisions.

In making such a carriage, it is not important to make the grooves N and U very *straight*, but it is important to make them very *smooth*. So if you cut them on a machine, finish them with a fine file or hone.

The focusing carriage is clamped to a leveling table (not shown) so that the line of travel of the Z-disk can be pointed exactly along the ray from the center of the mirror.

The Zernike Disks: I make my Z-disks by squashing spheres of resin—preferably softened with a few percent of turpentine. In the following account of the process, I shall quote extensively from a paper "On the Phase Contrast Test of F. Zernike"—*Monthly Notices* of the R.A.S., March 1934—with trifling alterations for brevity.

"Spheres of all sizes from 0.05 to 0.001 mm. diameter or less, are precipitated when a 5 percent solution of resin in acetone is poured into 20 times its volume of water. Those that remain in suspension for 12 hours may be rejected as too small: those that settle in one hour are too big. I find it best to distribute them on the microscope slide in water. The procedure is: Dilute the suspension till it looks only faintly milky: pour a few drops on to a clean, dust-free slide, and shake off the excess. Allow the remaining film to dry before putting the cover-glass on. If you put the cover-glass on while the film is wet, the surface tension of the water tends

to pull the globules into chains during the drying process. Precautions should be taken to keep out dust while assembling the slide, and it is advisable before distributing the globules to obtain Newton rings between slide and cover-glass—in doing so one crushes foreign matter which the cleaning process has failed to remove."

It is desirable to select a cover-glass which fits the slide closely—as shown by the Newton rings. The cover-glass must next be tacked to the slide with Canada balsam, to prevent it moving laterally during the pressing. If it moves laterally, even during the tacking, many of the globules will be smeared and spoilt.

To prevent this, lift up the free end of one of the spring clips on a microscope stage, and lay the slide underneath it. Then let down the spring clip very gently on to the cover-glass. The cover-glass may then safely be tacked round its edge with a small quantity of balsam, applied on a thin rod. It is advisable to let the balsam dry for an hour before pressing.

To press the spheres into disks, look at them through the microscope, with a low power (1″ or ⅔″) objective, and press the cover-glass over each sphere in turn, with a metal rod—pointed, but not pointed enough to scratch the cover-glass. A medium or fine steel knitting needle will do.

Do not attempt to press each sphere quite flat at once (or you may crack the cover-glass) but go over the whole slide several times, increasing the pressure until you see Newton rings (in white light) while the pressure is applied.

If you press finally as hard as you dare, it is unlikely that you will press the disks too thin. The cover-glass usually springs up when the pressure is relaxed, but if there is not too much turpentine in the resin, the globules do not stick to the cover-glass, and so are not torn. If there is too little turpentine, they may crack.

You will see many Z-disks appear, due to the squashing of spheres too small to be seen unsquashed. The aperture stop on the microscope substage condenser should be closed down considerably, otherwise the Z-disks will be difficult to see, owing to their transparency.

"In this way one produces a slide containing perhaps 100 Z-disks, ranging from 0.02 to 0.002 mm. diameter, many of them of the right order of thickness, and reasonably circular. . . . The considerations which follow will provide a means for ascertaining from the appearances seen on the test itself whether a given Z-disk is a good one or not, so that while it is convenient to inspect the Z-disks with a microscope during their manufacture, it is by no means essential to pick out a good one, with a microscope, and ensure that that Z-disk, and no other, is used for the test." No doubt one could make them without a microscope—though I should expect the percentage of failures to be higher.

The Test Procedure: "The slide of Z-disks is set (with the cover-glass facing the mirror) several mm. out of focus, and the observer, with his eye close behind the image, looks at the illuminated mirror. As he moves the

centering screws, so as to traverse the slide across the cone of light, he will see circular patches, surrounded by rings, moving across the mirror. Each of these is the system of interference fringes created by a Z-disk: there is no difficulty in finding them, because the slide contains very many Z-disks. One is centered, and the focusing track is leveled and adjusted in azimuth, so that its fringe system stays central as the Z-disk is taken through focus. It will be noticed that the Z-disks are not all identical, the fringe systems which they give differing in the color of the central patch, which may be almost any color, weak or strong, or neutral tint, or simply brighter than the general level of intensity of the rest of the mirror. They differ also in the number of rings which can be discerned surrounding the central patch."

Our slide, in fact, contains many blobs of resin, *some* of which *may* be worthy of the name of Z-disks. We have to choose a good one.

Theory of the Test: To know a good Z-disk when we see it—or rather, when we see the fringe system it creates on the mirror—we must understand how and why the test works. This has to do with the wave properties of light, and we shall have to use in our explanation three of those properties:

The first is the Principle of Superposition, which states that if two waves, A and B, approaching a surface from the same side, produce all over that surface, when they act together, the same effect that a wave C (approaching the surface from the same side) would produce, when acting alone, then the effect of A, propagating by itself, plus the effect of B propagating by itself, will everywhere equal the effect of C propagating by itself. And this equality holds, not only at all points to which the waves go, but also for all points from which they might have come.

We apply this principle by calling C the wave that actually emerges from the Z-slide, and A the wave that would have emerged, had the Z-disks not been there. Then, by the Principle of Superposition, we are allowed to say that the wave from the mirror, A, propagates into our eye as though the Z-disk were absent, but that in its passage through (and around) the Z-disk, it creates a supplementary wave, B $(= C - A)$, and that this wave propagates independently into our eye. When it reaches our retina, it interferes with the wave A, and so creates the Zernike fringes, $A + B = C$.

Since we focus our eye on the mirror, we shall see the interference as if it occurred on the mirror, between the wave A as it was when it left the mirror, and the wave B, as it would have had to have been, had it been created at the mirror, to give rise, in the absence of the Z-disk, to what it actually is when it leaves the Z-disk. That is, we shall see the interference between the wave A and the *virtual wave* B, at the surface of the mirror.

Now, it is easy to form a picture of the wave B, just as it leaves the Z-disk: it is obviously zero except inside a patch the size of the Z-disk. Inside this patch, its distribution of intensity is similar to that of the wave A, since B is the difference between A and A—delayed—by—¼ wave-length.

In fact, if n be the number of oscillations of the light per second, and t the time, so that we can write the amplitude of the wave A at time t as

$A \cos 2\pi nt$, the amplitude of (A delayed by a quarter wave-length) will be $A \cos 2\pi (nt - 1/4)$, and the amplitude of B within the area of the Z-disk will then be

$$A \cos 2\pi (nt - 1/4) - A \cos 2\pi nt$$
$$= \sqrt{2} A \cos 2\pi (nt - 3/8)$$

—the one piece of trigonometry without which it is hardly possible to explain the Zernike test. It has the very simple interpretation that within the area of the Z-disk, B is $\sqrt{2}$ A, delayed by three-eighths of a wave-length. Outside this area B is of course zero.

The next property of waves which we need is that of diffraction—the fact that waves continually try to spread sideways at their edges as they move. Thus the wave B after leaving the Z-disk, will spread out through quite a wide angle and, even if it started as a flat wave, would finally become an expanding approximately spherical wave, rather weaker at its edges than its center. And if the Z-disk from which B starts is a little smaller than the Airy disk produced by the mirror, B will expand throughout a cone a little wider than the cone of light supplied by the mirror. Clearly, if *B had* come from the mirror, it would have had to have started as an approximately spherical converging wave, a little wider than the mirror.

The third property of wave motion,—interference, has already been discussed (in the chapter by R. W. Porter, on "Optical Flats," "A.T.M.".) It is sufficient therefore to point out that when we look at the mirror, we shall see interference fringes formed between the wave A, leaving the mirror, and the virtual supplementary wave, B, which *was* created at the Z-disk, but *might have started* at the mirror, as an approximately spherical converging wave, a little wider than the mirror. And when the Z-disk is at focus, we shall actually see this "virtual wave," B, extending for several cm. outside the mirror, as a brilliant halo of light.

The interference fringes seen on the mirror tell us the *misfit* between the wave leaving the mirror, and the approximately spherical virtual wave, B, just as the Newton fringes between two flats tell us the misfit between the two waves reflected from their surfaces. If the virtual wave, B, was accurately spherical, the Zernike fringes would therefore show us the asphericity of the wave leaving the mirror.

We can use the Principle of Superposition to show that only a fraction of the asphericity of the mirror will be present in the wave B, so that the contrast with which the mirror's errors will appear in the interference fringes will be nearly as great as it would if B were accurately spherical.

For we can represent the wave leaving the mirror as the sum of two waves, S, a spherical wave which the mirror would produce if error free, and an "error-wave," E,E, being $A - S$, where A is the wave which actually leaves the mirror. At the mirror surface, then, the wave E is zero on those parts which are correct, and is strongest on the tops of the hills, or (with reversed sign) at the bottoms of the hollows. This wave cannot contract to form so small an Airy disk as does the spherical wave S, because it does not start (with full strength) from so large an area as the wave S, which

we have defined as coming from the whole of the mirror. Another way of putting this is to say that diffraction interferes more seriously to prevent the "error-wave," *E*, contracting to a point, because the wave *E*, starting only from inaccurate parts of the mirror, has a *greater periphery* from which spreading can take place, than the wave *S*. Thus, if the Z-disk is small, only a fraction of the wave *E* goes through it, so that the supplementary wave, *B*, created by the presence of the Z-disk, will only contain a fraction of the mirror's error, and when we look at the mirror's surface we shall see the errors in interference contrast nearly as great as if the wave *B* were accurately spherical.

If the "error-wave," *E*, starts from only a *very* limited part of the mirror (*i.e.*, if the error consists of a *narrow* high or low zone) the Airy disk of *E* will be very wide, so that most of it will fall outside even a very large Z-disk. But if the wave *E* starts from most of the mirror's surface (*i.e.*, if the error is a fairly slow one, such as simple spherical aberration or a slower one—coma—or a slower one still, such as astigmatism or "error" of absolute focal length (usually unimportant, so not called an error)) then it will contract to form an Airy disk nearly as small as that of the wave *S*. Then, unless we use a very small Z-disk, most of *E* will pass through the Z-disk, and will appear in *B*, and so will *not* appear in the Zernike fringes. But if we use a Z-disk that is too small, the wave *B* will be too weak compared with *A* to give strong interference colors. Thus this simple explanation does not *prove* that the test will be sensitive, except for rapid zonal error; it merely shows that *perhaps, with luck* it may also be sensitive for slow errors.

But Professor Zernike has made a very complete rigid mathematical analysis of the problem, which shows that before the Z-disk gets too small to show strong interference colors, it does in fact get small enough for nearly the whole of the "error-wave," *E*, from the slowest errors to pass outside it. Thus even the slowest error—astigmatism—will be shown with about as full contrast as it would be if the interfering wave, *B*, were accurately spherical. And this has been checked experimentally.

As each point on the surface of the star will give rise to a separate Airy disk, the source should clearly be as small as, and preferably smaller than, the central maximum of the Airy disk—otherwise we shall not be able to use a small Z-disk. That is why, for the Zernike test, you *must* use an exceedingly small source of light: a source which the mirror cannot resolve: a "star," in fact, and not a "major planet."

The reason why the Z-disk should retard the light ¼ or ¾ wave-length, and not (say) ½, is that then the supplementary wave, *B*, will have that separation from the wave *A*, leaving the mirror, for which the interference intensity changes most rapidly with small errors in the wave leaving the mirror. ¼ and ¾ wave-length retardations change the contrast with which an error is shown, in opposite directions, so that if—as is the case with many of my disks—the disk retards yellow light by ¼ and blue by ¾ period, we shall see the errors in color contrast—the hills in blue, and the hollows

in yellow. Thicker disks, giving green and pink, seem to be a little less sensitive.

The Test Procedure—continued: We have now all the data necessary to enable us to choose a good Z-disk. First, we can immediately say that those disks which give strong colors when some distance out of focus are certainly too large; for strong colors imply a strong supplementary wave (B). And this means that most of the light must be going through the Z-disk. But, if the Z-disk is comparable in size with the Airy disk, the only way to get most of the light through it is to center it on the Airy disk at, or very nearly at focus. To quote again from *M.N.,* R.A.S., "We must therefore reject those Z-disks which show brilliant colors some distance off focus, and choose one which shows very faint and ghostly fringes. It is convenient to specify the distance of the Z-disk from focus in terms of the apparent error of the mirror in interference fringes (half wave-lengths), temporarily assuming the 'true figure' to be that which would focus where the Z-disk happens to be: the merit of this specification being that the fringe system given by a Z-disk depends essentially on its number of fringes off focus, whatever may be the focal ratio of the image. (To convert mm. axial distance off focus into fringes of apparent error, divide 250 by the square of the focal number of the image: the quotient is the number of "fringes off focus" per mm. off focus: thus $F/16$ gives one fringe per mm. This assumes $\lambda = 5 \times 10^{-5}$ cm."

(A mirror diameter D, radius R,$=2F$ when tested at its center of curvature is *imaging* at a focal number $2F/D$—not F/D).

"We can now apply a second check that the Z-disk is small enough, for if we put it a *small* number, n, of fringes inside or outside focus, it ought to show just n concentric fringes on the mirror (unless the mirror errors exceed one fringe). If we make n large, we shall not see n fringes, for two reasons, first, because the source is not monochromatic, and the scale of the fringes depends on wave-length, and second, because of the finite size of the source, which destroys the visibility of the higher order fringes. One can just see the second fringe, with a 0.013 mm. source and an $F/8$ image (for which 0.013 mm. is really rather too large a source): with an $F/16$ image, about 4 fringes are visible.

At the same time we can check that the Z-disk is sufficiently circular. If the fringe system is circular both inside and outside focus, then the Z-disk is circular, and the mirror has no astigmatism. An elliptical fringe system can be due to astigmatism or to an elliptical Z-disk. But if the ellipticity is due to astigmatism, the major axis of the ellipse will be perpendicular to the focal line to which the Z-disk is nearest, so that if the ellipse is elongated, say vertically, inside focus, it will be elongated horizontally outside focus: on the other hand, if the ellipticity is due to the Z-disk, the major axis of the ellipse will have the same direction as the major axis of the Z-disk, and the fringe system will be elongated in the same direction both inside and outside focus.

Finally we have yet another check that the Z-disk is sufficiently small. If the Z-disk is smaller than the Airy disk of the mirror, the supplementary

wave to which it gives rise will spread through a wider cone than does the light from the mirror, so that we shall see the mirror surrounded by a halo of light, the outer diameter of which may be 50–70 percent greater than the diameter of the mirror. The intensity of the halo is proportional to that of the light traversing the Z-disk, so that the halo is only visible when the Z-disk is within a fringe or two of focus, and if the mirror errors exceed a fringe or two (so that 'focus' is indefinite) the halo may be too faint to be seen. A Z-disk that is too large gives a very narrow halo, unless it has inclusions or cracks: these may give a wide halo, but because of their irregularity, they give a secondary interference pattern in the halo, making it appear patchy. A large Z-disk with a small circular concentric inclusion would pass the 'halo' test of suitability, but would have been rejected on the previous tests. (I have not found a Z-disk of this type). Some Z-disks produce a colored halo—blue, green or red. . . . It is wise to reject a Z-disk giving a deeply colored halo."

"We can now consider the colors developed by the Z-disk on the mirror. When the Z-disk is, say, 3 fringes out of focus, the fringes will be faint and neutral tinted. But as it is brought nearer focus, colors will develop if it is of the right thickness. It will in general be found that the central color of the fringe system is not the same inside and outside focus: for example we may get blue and yellow or green and red, depending on the thickness of the Z-disk: this is the effect that a Z-disk which retards the phase of some colors by m $\pm$ ¼ periods produces. If the phase retardation is ¼ periods for all colors, the central inside focus "color" will be black, and the central outside focus "color" white: such a Z-disk can be used for the test, but I find it easier to work with one giving a contrast of tint rather than of amplitude. A Z-disk showing the same colors inside and outside focus should be rejected."

Actually, "black and white" Z-disks would probably be the best. But there are so few "black and white" ones on my slides that I do not think I have yet seen a good one—circular, and the right diameter.

"Select then a Z-disk showing a good contrast between its central inside and outside focus colors, *but above all do not select a Z-disk on account of its good colors unless the preceding tests have shown that it is sufficiently small: I cannot too strongly emphasize this point.*"

"If one uses a Z-disk that is too large, it will create a supplementary wave containing a part of the short period error, and nearly the whole of the long period error of the mirror, so that while it will show up local irregularity nearly as well as a smaller Z-disk, it will fail to show up long period errors—simple spherical aberration, and more especially the two errors of longest period—astigmatism, and 'error' of absolute focal position. A test with a Z-disk that is too large is in fact exactly like testing a flat with a straight-edge that sags under its own weight—the local humps show up, but slow curvature does not. Therefore even if one is not interested in determining the absolute focal position, it is essential to verify that a change of, say, ½ fringe in the focal position does change the fringe system by ½ fringe, as a proof that the Z-disk is small enough."

"If the errors do not exceed ¼–½ fringe, the interpretation of the test presents no difficulty, for by putting the Z-disk a fringe or so out of focus, one can superpose a general spherical error larger than the residual errors without making the colors too faint to identify, and one can even superpose an error of tilt by decentering the Z-disk when it is slightly out of focus: this is equivalent to the process of lifting one edge of a contact interference test-plate to see how the color sequence runs, but with the slight difference that if the Z-disk is inside focus we must imagine a hypothetical contact test-plate with its center attached to the Z-disk to be making contact to the outside of the mirror surface, this hypothetical test-plate being slightly convex with respect to the mirror, so that as the Z-disk is decentered, it rolls the hypothetical test-plate over the mirror, and the fringe system moves in the same direction as the Z-disk, expanding as it approaches a hill, and contracting when it gets to the top: contracting when it approaches a hollow, and expanding when it gets to the bottom. If the Z-disk is outside focus, we must imagine the hypothetical test-plate to be slightly concave with respect to the mirror, and to be making contact to the inside of the mirror surface from the back, so that as it is rolled over the back of the mirror surface, the fringe system moves in the opposite direction to the Z-disk, and the pattern contracts as it approaches a hill, expanding when it gets to the top: expands when it approaches a hollow, contracting when it gets to the bottom.

If one decenters the Z-disk at focus, the visibility of the fringes fades very rapidly, as it approaches the first zero of the Airy rings, and the supplementary wave is no longer created.

We have further the rule that the primary color developed centrally inside focus will be the color in which area up to about ¼ fringe high will show, when the Z-disk is at focus, and the primary outside focus color will be that in which areas up to about ¼ fringe low will show."

"Let us take as an example a test on a spherical speculum 12.5 cm. diameter, 200 cm. radius of curvature. When the chosen Z-disk was set 3 fringes inside focus, three fringes showed in faint nondescript colors, the third being so faint as to be just distinguishable. When it was set ½ fringe inside focus, it produced a halo round the mirror, extending to about 18 cm. diameter. The fringe system on the mirror consisted of a blue central patch, outside which the color shaded through neutral tint into a deep tawny yellow, which in turn shaded into a very pale yellow near the edge of the mirror. The fringe system was not exactly circular—traces of the residual error could in fact be seen 'through' the ½ fringe focusing error. When the Z-disk was set ½ fringe outside focus, the central patch was deep tawny yellow, surrounded by neutral tint shading into blue-white and to very pale yellow near the edge of the mirror: traces of residual error marred the precise regularity of the system.

When the Z-disk was set at focus, neither the blue nor the deep tawny yellow were fully developed on any part of the mirror: there were, however, irregular patches where the neutral tint which covered most of the mirror shaded into a very weak blue or tawny yellow. From the appearances ½

fringe inside and outside focus, I interpret the color sequence for this Z-disk when at focus as follows:

Very pale yellow to deep tawny yellow	½ to ¼ fringe	low.
Deep tawny yellow to neutral tint	¼ to 0 "	"
Neutral tint to blue	0 to ¼ "	high.
Blue to very pale yellow	¼ to ½ "	"

The patches, where with the Z-disk at focus, the neutral tint changes to weak blue or tawny yellow, I interpret as being about ⅛ fringe high or low." (0.1 fringe = roughly 10^{-6} inch).

"I have done a Michelson test on this mirror, and did not find more than ± 0.1 fringe error. I had of course seen the existence of these errors with a knife-edge test, and indeed had reduced them to their present value, testing with vertical and horizontal knife-edges in succession. But the interpretation of irregular error from a pair of knife-edge tests is by no means easy, especially when one is nearing the limit of sensitivity of the test, and I was not sufficiently certain of the interpretation to continue the local figuring.

The great value of the Zernike test is, not that it may be somewhat more sensitive, nor even that it is free from the disadvantage of producing logarithmically infinite illumination at the edge of the mirror (the "Rayleigh ring" of the knife-edge test), but that no matter how complicated the errors may be, provided they are not too large, the colors indicate the errors themselves, and not the slope of error in some particular direction."

It should be remembered that the test will show the astigmatism consequent on the lateral separation (2δ, say) between the star and its image. This will produce a longitudinal astigmatism (*i.e.,* distance between focal lines) of amount δ^2/F. Expressing δ^2/F in mm. and multiplying by $250\left(\frac{D}{2F}\right)^2$ gives the apparent astigmatism in interference fringes. For example, with the speculum discussed above, $\delta = 2.24$ cm. produces ½ fringe of astigmatism, and gives a Zernike fringe pattern consisting of a broad band of blue (high) bordered above and below by deep tawny yellow (low) when the Z-disk is set at one focal line, or, when it is set at the other, a perpendicular broad band of deep tawny yellow, bordered to left and to right by blue. The deliberate introduction of astigmatism forms an excellent check on the sensitivity of the test.

It is possible to use the test zonally *if and only if* the mirror's asphericity is very small. To quote from *Monthly Notices* of the R.A.S., April 1935:—

"A black scale, the divisions of which are small teeth, projecting from a narrow strip, is supported across a diameter of the mirror. When a Z-disk is centered, and is sufficiently near mean focus, the scale-teeth appear brightly lit. . . . Accordingly one sees the luminous scale cutting across a concentric system of Zernike fringes. The zonal measurement consists in determining the focal settings of the Z-disk which cause the lowest order of interference present to pass through, or midway between, successive pairs of scale-teeth.

The color of the ring representing the lowest order of interference changes slightly as its diameter is increased by moving the Z-disk from paraxial to marginal focus, because the order in question changes, so that it is not a case of watching the diametral growth of a ring of given color, but the growth of a ring surrounded externally and internally by a color sequence representing increasing orders of interference—*i.e.*, increasing apparent lowness of the mirror's surface. The mirror is not diaphragmed for the zonal measurements. The scale is removed while the paraxial setting is made."

The focal settings of the Z-disk so obtained may be interpreted—*if and only if it is sufficiently small*—as though they were focal settings of a knife-edge, obtained with only the zone in question exposed. But a Z-disk, small enough to give a good test on a spherical mirror of the same focal ratio "will give fringes heavily diluted with uncolored light if the asphericity of the paraboloid greatly exceeds half a fringe with respect to the sphere contacting it at the center, and cutting it at the edge—*i.e.*, if the diameter of the paraboloid in cm. exceeds one twentieth of the cube of its focal ratio."

This limit, $D\ cm < \frac{1}{20}\left(\frac{F}{D}\right)^3$, is, if anything, not severe enough. If an oversize Z-disk is used, to gain fringe contrast, theoretical doubts arise about the interpretation of the results.

The Limit of Sensitivity of the Test: Professor Zernike has shown that when the Z-disk is at focus, a perfect mirror would not show an *absolutely* uniform intensity in monochromatic light. (This is because the supplementary wave, p. 95, is a little weaker at the edges). It would show greater uniformity when the Z-disk was a little off focus.* Now Z-disks such as I have described, giving chromatic dispersion of retardation, would need to be pushed inside focus to secure greatest uniformity in one color, and pulled outside, to secure it in another. Since they cannot be displaced simultaneously both ways from focus, they must always give a greater intensity of one or both colors, at the center. Thus with a perfect mirror, when such a Z-disk is at focus, the edge looks *neither* high *nor* low, but the center looks *both* high *and* low simultaneously. Clearly, as soon as this effect becomes at all prominent, the real limit of the test has been reached. From the ease with which an "artificial error" of 0.09 fringe can be shown (this error being introduced by a figured plate put in the line of sight), I am inclined to set this limit at between 0.05 and, say, 0.02 interference fringe.

[Editor's Note: Some items stated by the author in a personal communication may be of interest. "Prof. Dr. F. Zernike is Professor of Theoretical Physics at the Rijks Universiteit te Groningen, The Netherlands. Besides inventing the Z-test, he applied it to the microscope—not to test the lenses but to 'test' the object under examination. Germs, for example, being (when alive) transparent things having very nearly the same refractive index as the surrounding medium, are difficult to see, and in fact are invisible when you

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* A mirror that showed *absolutely* uniform intensity would, however, only be aspherical by an extremely small amount—about 0.01 fringe.

focus the microscope directly on them. To 'see' them, you have to put the microscope a little out of focus, and then you see them in the same way that you can see rapid zonal error. With Z-illumination you can see them as if they were stained black, when you focus exactly on them. Z-illumination for the microscope is a subject well worth study, but it needs a two-man team, consisting of a pathologist and physicist. Because the germs or living cells (e.g., fibroblasts, which are good Z-material) correspond to very rapid zonal error, it is permissible to use an enormous Z-disk, and he uses one ½ mm. in diameter, which he makes by etching a depression on a glass plate. Etching is hardly practicable for 0.01 mm. disks—that is why I had to devise the resin technic. I hope some American pathologist and physicist will have a shot at it. I should be very glad to put my small experience at their disposal."

If there is a pathologist among the telescope making fraternity, this is his bid; perhaps he can render visible the virulent germ of the telescope making disease, which has never been isolated.]

A Quantitative Optical Test for Telescope Mirrors *

By J. H. King
Amityville, New York †

Several methods have been proposed and used in the testing of optical surfaces. Among these the Foucault knife-edge test is the most popular as it is visual and requires only simple apparatus. The Hartman test, being photographic, is used where a final analysis of the performance of an optical instrument is desired.

About 1923, Vasco Ronchi proposed a method of testing, which has the appearance of an interference method but involves only simple apparatus.[1] J. A. Anderson and R. W. Porter have found the Ronchi test to be fully as sensitive as the Foucault test and, under favorable conditions, capable of showing an error as small as $\frac{1}{10}$ of a wave-length in the wave surface leaving the principal plane of the instrument.[2] However, the Ronchi test is only qualitative as it does not indicate the amount of aberration present.

While considering the theory of the Ronchi test, and wishing that it were also quantitative, the writer discovered a simple scheme using this principle with the addition of a very simple auxiliary apparatus, which resulted in a quantitative test.

Quantitative Feature of Test

The feature, making the test quantitative, consists in superimposing two fine parallel line images, which serve as gages, on the lens or mirror under test. The Ronchi grating is reduced to a single wire alined with the gage lines and the optical slit. By moving the wire axially its shadow image is symmetrically expanded until it crosses the fixed gage images at the zonal radii under test, the displacement necessary being a measure of the aberration existing between these zonal radii.

The exact method of forming the line images on the mirror is not important so long as it does not introduce errors larger than those of measurement. The method that first occurred to the writer was to stretch piano wires immediately in front of the speculum and view them by the diffraction around their edges or illuminate them by a light of contrasting color from one side. In the case of testing mirrors where the back (not the optical surface) of the mirror is polished and reasonably plane, a cardboard screen, placed against the back of the mirror, having the gage slits and markings indicating the zonal radii cut in it and illuminated from behind, would be very simple and perhaps could not be surpassed. The method to be described produces virtual gage line images against the speculum by the use of a small glass diagonal and has the advantage, that it is more generally applicable especially where the lens or mirror may be mounted in an inaccessible place. The distortion produced by the use of a small parallel glass diagonal in

* Reprinted by permission, from the *Journal of the Optical Society of America*, Sept. 1934

† Member Technical Staff, Bell Telephone Laboratories, Inc.

1 Vasco Ronchi, *La Provi dei sistemi ottica*, Bologna, 1925

2 Anderson and Porter, *Astrophys. J.* 70, 175 (1929)

having the cone of rays from the speculum pass through it is probably small, since the diagonal need be nothing larger than a microscope slide cover glass and can be placed very close to the eye. It may even be placed behind the test wire right next to the eye.

Apparatus and Procedure

The set-up of apparatus is shown in the sketch of Figure 1. Here we have at *B* an optical slit from which the rays of light emanate, strike the

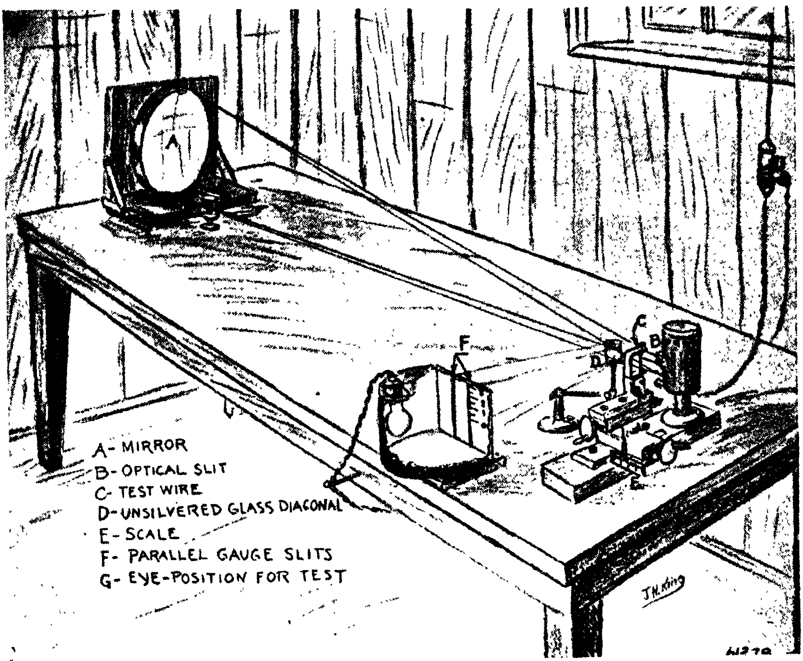


Figure 1

speculum *A* (under test) and return to focus at *G*, the position of the eye for the test. Immediately in front of *G* is placed a tensioned wire *C*, arranged symmetrically in the returning cone and parallel with the optical slit. (The writer has used a wire about 0.006″ in diameter.) An unsilvered diagonal *D* reflects the image of two parallel gage slits *F*, allowing them to be viewed at *G*, and appear symmetrically superimposed on the speculum *A* along with the shadow image of the test wire. The scale *E* is used in measur-

ing the displacement of the wire C along the axis of the returning cone.

The procedure consists of adjusting the gage slits until they appear as separated about ¼ or ⅓ the diameter of the speculum and then leaving them fixed. The test wire is then adjusted along the axis until its shadow image appears to just touch the gage images as in *a* of Figure 2. The reading on the scale E, Figure 1, is then noted. The wire is again moved along the axis until its shadow image intersects the gage slit image symmetrically at zone r_2 as in *b* of Figure 2. The reading on the scale E is again noted. The difference between the two scale readings measures directly the aberration

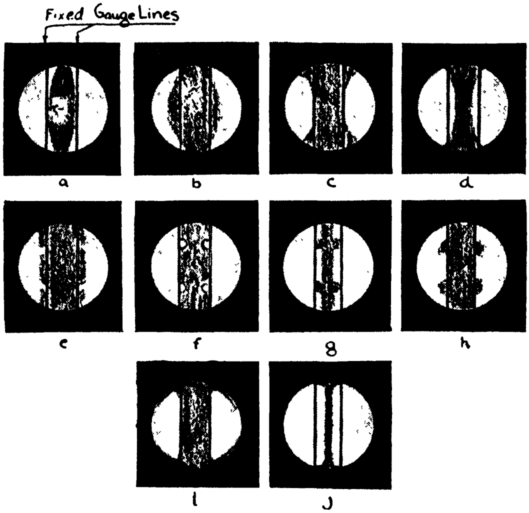


FIGURE 2

existing between zone r_1 and r_2. Likewise, the remainder of the mirror outside zone r_1 may be tested with the gage slits fixed. Should it be desired to test quantitatively inside zone r_1, the gage slits should be moved closer together and the above procedure repeated.

GEOMETRY OF TEST

Figure 3, *a*, shows a horizontal plan view (not the conventional vertical section through an optical system) of the test when adjustment is made for zone r_1 as in *a* of Figure 2 and shows only the rays proceeding from zone r_1 to focus. Similarly, *b* of Figure 3 shows the plan view of the adjustment for zone r_2. In *a* of Figure 3, y_1 is the distance that the test wire C of Figure 1 is situated in front of focus to appear to just touch the gage slit images. The distance that the wire C, Figure 1, is situated in front of focus for zone r_2 is designated by y_2, the shadow image of the test wire C appearing, in this

case, as in *b* of Figure 2. Δy is the distance test wire C is moved to effect these two conditions. Since in *a* and *b* of Figure 3, angles α_1 and α_2 are equal (within limits affecting this test), it follows from substantially similar triangles that $y_1 = y_2$ and Δy measures directly the aberration existing between these two respective zonal radii. In the case of testing a spherical mirror at its center of curvature, Δy is equal to two times the difference in radius of curvature of the zones providing the optical slit remains fixed.

Before discussing the appearance of some common forms of aberration in this test, it might be well to state, that the shadow image is not quite as

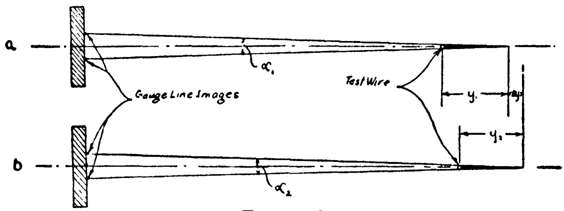


FIGURE 3
Horizontal plan views—looking down on test from above.

shown in the sketches. With a wide optical slit, the shadow image of the test wire is not sharp on the edges, while a narrow slit causes secondary diffraction effects to appear. The fine slit adjustment seems preferable, since it gives the sharper shadow image to the test wire. Too fine a test wire (0.001″ diameter) does not apparently improve the sensitivity of the test, since then the wire has to be brought very close to focus to expand its shadow appreciably, again making it difficult to preserve a sharp shadow image. However, in spite of the above, the writer has been able to duplicate measurements at least as accurately as with the Foucault test. The test is much faster than the Foucault test when the latter is used with zonal stops and at the same time the qualitative feature of the Ronchi test is always observable.

Appearances of Common Forms of Aberration

In *c–d, e–f, g–h* and *i–j* of Figure 2 are shown some common forms of aberration as they appear in this test. Aberration of the opposite sign to *a–b* of Figure 2 is shown in *c–d,* the former being the case of outer zones too long in focus, and the latter, outer zones too short. The appearance of a raised zone is shown in *e–f* of Figure 2, and *g–h* shows a depressed zone at the same place on the speculum. Turned edge, one of the worst enemies in the figuring of optical surfaces, is easily detected and can be accurately analyzed by this test. In all other tests the wire C, Figure 1, has been kept just inside of focus but in the case of turned edge the sketches Figure 2 *i–j* show the appearance of placing the wire just outside the focus as this gives more prominence to the effect. In quantitatively testing parabolic

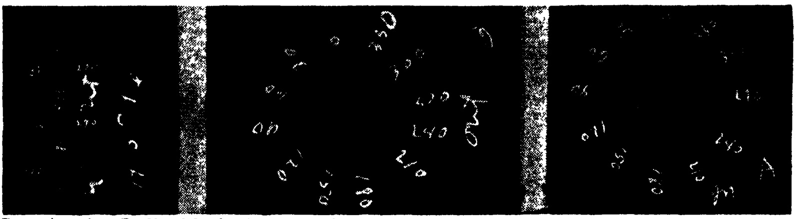
mirrors of short focal ratio at the average center of curvature, the Foucault shadows become very deep, necessitating the use of a large number of zonal stops. The present test would seem more suitable in such cases since the use of stops is eliminated and photometry is unnecessary.

[EDITOR'S NOTE: Alan R. Kirkham of Tacoma, Washington, Franklin B. Wright of Berkeley, California, Loren L. Shumaker of Dayton, Ohio, and possibly others, were working on the same problem—making the Ronchi test quantitatively—at about the same general time as Mr. King, and each developed his own method. Mr. Wright's was published in a *Supplement* to the *Bulletin of the Eastbay Astronomical Association;* Mr. Kirkham's was offered the *Scientific American* and was accepted, but publication was delayed through the present writer's dilatoriness; Mr. Shumaker's was distributed privately in a multigraphed circular.]

The Hartmann Test

By William A. Calder, Ph.D.
Harvard College Observatory, Cambridge, Massachusetts

The standard observatory method of grading the performance of large mirrors and objectives is the Hartmann test. In general procedure and simplicity, the Hartmann and Foucault tests bear a close resemblance. Both seek to find to what extent the light of a star can be brought to a point; to do this, both locate the points of intersection of various pairs of light beams coming from definite points on the surface of the mirror. It should be emphasized that the Hartmann test is primarily a critique of the finished mirror rather than a guide during the process of figuring. Being more



Drawing by J. F. Odenbach, after the author

FIGURE 1

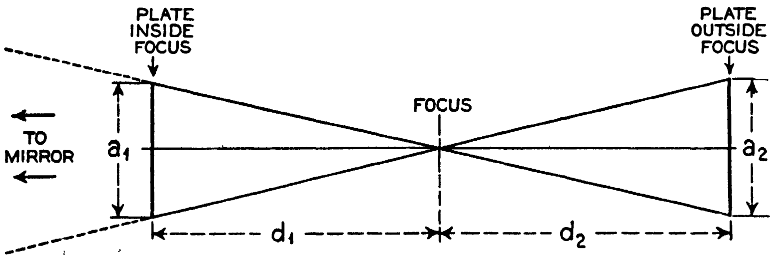
Left: Plate made photographically from 24" mirror. Center: Plate for 61" mirror—extra-focal position: pattern compressed toward center. Right: Plate for 61" mirror, inside of focus: pattern expanded. In each case, note the extra hole at the top; this is cut in the screen which is placed against the mirror, to identify the zero position on the photographic plate. For a fairly large mirror the holes are made about ¾" or so in diameter.

laborious than the Foucault, it is frankly less adapted to the needs of the amateur. Nevertheless, as a slightly different approach to the central problem of mirror making, it is of more than general interest.

Let us consider first the simplest case, namely, the test of a parabolic mirror under actual working conditions, the light source being a star on the optical axis of the telescope. With a perfect mirror (and perfect "seeing") the light from all parts of the mirror comes to one focus, the individual rays all intersecting at one point on the axis. Now suppose that we cover the mirror with an opaque screen in which a series of holes is punched along various diameters of the mirror. The holes will be in pairs, so that each pair is accurately centered with respect to the mirror. If we place a photographic plate considerably inside the focus, upon exposure to the star we shall obtain a pattern similar to the array of holes in the screen, since the individual bundles will have not come to the intersection. Similarly, we shall get another pattern with the plate placed out beyond

the focus. Figure 1, at left, shows the patterns obtained with the Harvard 24″ reflector under this kind of experiment.

We now confine our attention to the light bundles from a single pair of holes on one diameter, say the holes for a radius of 12″, where a_1 and a_2, Figure 2, are the separation of the images on the two plates, as measured with a comparator (microscope micrometer) and d_1+d_2 is the separation of the emulsion in the two positions of the plate. d_1 is thus the focus of the two areas of the mirror with which we have been concerned, referred to the inner position of the sensitized surface of the plate. We next compute the



SINCE WE HAVE SIMILAR TRIANGLES, $\dfrac{a_1}{a_2}=\dfrac{d_1}{d_2}$, $\dfrac{a_1}{a_1+a_2}=\dfrac{d_1}{d_1+d_2}$, $d_1=\dfrac{a_1(d_1+d_2)}{a_1+a_2}$

FIGURE 2

position of focus for all other pairs of apertures along the same diameter, so that we may find the mean (or average) focus. But since the area and hence the effectiveness, of each zone is proportional to its radius, we "weight" the mean [1] accordingly. Thus if there are n zones

$$Fo = \frac{R_1f_1 + R_2f_2 + R_3f_3 \ldots\ldots + Rnfn}{R_1 + R_2 + R_3} = \frac{\Sigma Rf}{\Sigma R} \qquad 2$$

If there are imperfections in the mirror, it will be impossible to obtain a point image in any position of the plate. The optimum position will be at the mean focus derived above. By similar triangles, the radius of the

[1] In taking a representative average, it is always necessary to give emphasis to various elements in accordance with their effect on the result. The simple average focus of all zones of a mirror is found by adding the individual foci and dividing by the number of zones. But the inner zones are of relatively little importance. Hence, in finding a significant value of the average focus, we "weight" the value of the individual zones, in this case by multiplying each by the radius of the zone.

[2] The symbol Σ (Sigma) is the short notation for "sum of." There is nothing highbrow about it, and its meaning is readily inferred from the first equation in which it occurs. Likewise,

$$\frac{\Sigma R^2(f - Fo)}{\Sigma R} \text{ means } \frac{R_1^2(f_1 - Fo) + R_2^2(f_2 - Fo) + \ldots + Rn^2(fnFo)}{R_1 + R_2 + \ldots\ldots\ldots\ldots + Rn}$$

image disk at any focus f is $rd = \frac{R(f - Fo)}{Fo}$

R being the radius of the mirror zone in question. The weighted mean of the radii of these scatter disks is

$$r_d = \frac{\Sigma\, R\, rd}{\Sigma\, R} = \frac{1}{Fo} \quad \frac{\Sigma\, R^2(f - Fo)}{\Sigma\, R}$$

As seen from the apex of the mirror, this average disk subtends an angle $\frac{1}{Fo^2} \frac{\Sigma R^2(f - Fo)}{\Sigma R}$ in radians,[3] or $\frac{206,265}{Fo^2} \frac{\Sigma R^2(f - Fo)}{\Sigma R}$ in seconds of arc.

"Hartmann's criterion" is defined as $\frac{200,000}{Fo^2} \frac{\Sigma R^2(f - Fo)}{\Sigma R}$ from which it is seen that the criterion is approximately the angular size of the radius of the circle of least confusion. We can at once compare the size of the best image with the resolving power of the instrument, or the scale of the plate. It is generally considered that, for a good mirror, Hartmann's criterion must be something less than 0.5.

By comparing the mean foci along various diameters of the mirror the astigmatism is determined. The Hartmann test may also be made at the center of curvature with an artificial star, just as the Foucault test. In this case, the patterns on the plate are not exactly similar to the array of holes in the screen, being compressed toward the center in the extra-focal position, and vice versa (Figure 1, middle and right, respectively). This is due to the distribution of foci along the axis, as given by the $2\, Fo + \frac{R^2}{2F} + \frac{R^4}{16F^3}$ equation. Comparison is made of the observed and theoretical distributions, care being taken to make the fit at a weighted mean position. Deviations in this case are four times as great as those made at the primary focus with parallel light, which must be taken into account in computing the Hartmann criterion.

The Hartmann test is applied to object glasses, but color filters must be used, since chromatic aberration would render the images too diffuse for measurement. The performance of the lens in various spectral regions is effectively studied in this manner.

An excellent account of the application of the Hartmann test of the 72″ Dominion Astrophysical Observatory at Victoria is given by J. S. Plaskett in Publ. Dominion Astrophysical Observatory, Vol. 1. This will be of interest because of the insight given regarding the construction of a very large reflecting telescope.

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[3] For convenience in mathematical treatment, it is frequently better to measure angles in radians rather than in degrees. A radian is the angle subtended by an arc equal to the radius; one radian is approximately 57⅓°. One radian is likewise equivalent to 206,265 seconds of arc. This is a very useful relation to remember in connection with small angles. An object observed to subtend one second of arc must have a size which is 1/206,265 its distance, and proportionately.

To summarize: In testing a mirror by the Hartmann method, a zone plate with radially symmetrical holes is placed before the mirror. A photograph is taken inside and outside of focus, with especially measured positions of the plate in the two cases. By measurement of the plates the performance of the mirror is easily found by simple geometry, inasmuch as any pair of holes along a given diameter of the mirror, and its corresponding images on the plates, locate the focus of a portion of the mirror.

Flats

By Horace H. Selby

It has been said that a true plane "is the most difficult of all surfaces to make."[1] Whether or not this is true, it is most certainly a fact that a large flat which is within 0.1 fringe of plane, including the edge, and which is completely free from pits, sleeks and scratches, is a truly difficult object to construct. In comparison, a high-quality paraboloid of equal size of aperture ratio 6 or 8 is easily made.

In the following paragraphs only those methods and materials will be discussed which have been used by the writer and which have proved satisfactory. It must be emphasized that, in other hands, other procedures have yielded equal or superior results and that no one can have a monopoly in the matter of technic.

Raw Materials

Polished plate: This is the usual material employed by amateurs. For most applications it is entirely suitable. In thickness greater than ¾", harmful strains may be encountered. It is rather soft (4.5—5.6 Mohs) and scratches easily. The high linear expansion coefficient (8.8—9.2 x 10^{-6} per °C.) makes testing time-consuming and temperature effects in use serious.

Pyrex:[2] For applications in which light does not traverse the flat this material is superior to polished plate. Scratches are less easily formed, due to greater hardness (6.2 Mohs). Disks of all sizes are uniformly free from large strains in the type designated as "Telescope Blanks." Sight glasses and sheet Pyrex are not so satisfactory in this respect. The low expansion coefficient (3.2 x 10^{-6}) helps to make testing and use easier and more reliable than with plate. Bubbles, striæ and stones must be expected.

Fused quartz:[3] This rather expensive medium is excellent for the construction of 10" and smaller test planes and standard flats. It is hard (7.0 Mohs) and changes but little with varying temperature. (Exp. 0.54 x 10^{-6}).

"Black" glass:[4] Many types of opaque glasses are sold for building decoration, counter tops, etc. They resemble plate in hardness and in expansion but some are not annealed and are useless for optical work. As test planes on which to examine other flats, for moon diagonals, polarizing mirrors and Colzi sun oculars, the deep color forms a background against which fringes appear with great brilliance and which reflects only a small amount of the incident light.

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1 R. W. Porter, "A.T.M.," page 16.
2 Corning Glass Works, Corning, N. Y.
3 General Electric Co., Schenectady, N. Y.
Thermal Syndicate, Ltd., Brooklyn, N. Y.
4 Wells Glass Co., Kokomo, Ind.
Pittsburgh Plate Glass Co., Pittsburgh, Pa.

Filter glasses: These are colored glasses which transmit restricted portions of the spectrum. They vary greatly in working qualities. Such glasses can be obtained from Corning Glass Works, Chance Bros., and Schott & Genossen. They are obtainable both "raw" and polished. The polished grade usually has a surface figure similar to plate.

Special materials: There are many optical and other instruments which utilize flat surfaces on mirrors, lenses, prisms and gratings of other materials, such as dozens of types of optical glass, various metals and such minerals as fluorite, sylvite, rocksalt, calcite, crystal quartz, etc. These materials require such special methods of working that they cannot be considered here.

Grinding abrasives: For surfacing, edging and perforating flats, Carborundum grains and powders are quite suitable. The writer uses Nos. 70, 150, 280, 400 and 600. Although more rapid and harder abrasives, crushed steel and carbides of tungsten and boron,[5] are available, they need not be considered, since no excavation is performed in flat-making. For finish grinding the finest emeries of Bausch and Lomb (906E) and the American Optical Co. (M303½) leave little to be desired. For even finer finishing the best talc may be mixed with the emery 50 percent by weight or the metallographers' Levigated Alumina[6] may be used.

Polishing abrasives: The oxides of tin, manganese, chromium, silicon, aluminum and iron have been used for various types of polishing for years. Of these, the iron and manganese oxides are the best for precise optical work. Manganese dioxide of proper purity and fineness is not readily obtainable; so the iron oxides—red and black "rouges" must be employed. The best "India Red Optical" rouge of Bausch and Lomb and the Spencer Lens Co. and the "Clark Grade" rouge of Alvan Clark and Sons Co. are excellent for final polishing and figuring. An occasional lot of black rouge is also suitable. For preliminary polishing, the rouges of the American Optical Co., Hanson, vanWinkle and Munning, and Binney & Smith serve well. It is more than worth while to wash and elutriate all rouge before using.

Laps: The same types of laps can be used on flats as on telescope mirrors. The HCF lap may be used for preliminary polishing, on all flats, but for precise plane mirrors to be used for testing paraboloids and telescope and photographic objectives the surface produced is unsuitable and pitch should be used for the final work. Ellison's criticism of paper and cloth laps[7] does not apply to flats since no curves are worked, and hard cloth laps, made as Orford recommends[8] can be made to yield flat surfaces at least as good as those produced with HCF. Plaster, glass, hardwood or iron may be used as a base for pitch laps. For machine work, wood and iron are distinctly superior.

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[5] The Norton Co., Worcester, Mass.
[6] Eimer & Amend, New York, N. Y.
[7] "A. T. M.," page 369, 3rd and 4th editions.
[8] "Lens Work for Amateurs", 1932, pp. 52–55.

Preliminary Work

If precision of a high order and permanence of figure are to be attained, the material of which a flat is constructed must be free from large strains. It is well to examine the strain figure of the material immediately upon receipt, before performing much work so that the pieces, if at fault, can be rejected, reannealed or discarded. The testing is easily done by the method outlined in "A.T.M."[9] With Pyrex and fused quartz, the faces should first be ground approximately plane and partially polished. Although this consumes time, it is the writer's opinion that it is well worth while. Unfortunately, the truly opaque glasses cannot be tested in this way. The visually opaque ultra-violet and infra-red filter glasses can be examined photographically by setting the analyser as for visual work, placing the specimen and substituting a camera, focussed for infinity, for the eye. Of course, an emulsion sensitive to the transmitted band must be used and the lens must be shielded from extraneous, unfiltered light. In general, photographic lenses transmit sufficient radiation for the purpose, even when testing the densest ultra-violet combinations. Exposures are long in some cases, running as high as six hours for a Corning infra-red filter, 4 mm. thick, using Eastman type I-M plates, hypersensitized, and tungsten illumination. As an excellent substitute for the Nicol prism used for strain-testing, the small (40 mm.)

Figure 1

Left: Edging, with two disks of ¼" plate pitched to the glass. Right: Polished edges. Flats of 4", 6", 8" and 12" diameter, photographed to show edge polish. The first, third and fifth flats from the left are Pyrex, the three smallest are extra-dense flint, the others plate.

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[9] Page 463, 3rd and 4th editions.

Polaroid[10] can be used, as can the more costly Herotar of Zeiss. They are cheaper and offer the advantage of large aperture.

The next steps to be considered are edging, parallelizing of faces and perforation. The edge of a flat can be ignored or it can be ground and polished. It is purely a matter of taste. Sometimes it is convenient to edge more than one disk at a time. Two disks of 1/4" plate can be pitched to the glass to avoid chipping, as shown below in Figure 1, left. Nos. 70, 150 and 280 Carborundum can be used on a wheel of boiler plate, 8" × 1/2", turning at 1800 r.p.m. with safety, but the finer sizes are better used on tools of wood, cut to size and faced with strips of 1/4" plate, held in pitch. The tools can be operated by machine if run between guides and held to the work by spring pressure, but the linkage is rather complicated. The same tools, faced with pitch alone, are used for polishing. Channels should be perpendicular to the faces of the disks, or cut diagonally to avoid polishing in rings. HCF is not suitable for this purpose. In edging with a spinning disk of metal, a great potential hazard exists. It is wise to provide heavy wooden guards and to stand clear of the wheel when running. The failure of a shaft, flange or wheel could inflict a serious injury.

Parallelizing the faces is a necessity if sextant mirrors, filters, interferometer planes, transparent diagonals or echelon plates are to be made. This is first done by the obvious method of flat-grinding one face of the disk, then cutting down the opposite elevations with small tools until micrometer calipers indicate the same thickness at many peripheral points and a true straight-edge makes light-tight contact with several diameters of both faces.

When it is desired to perforate a flat several precautions should be observed. Strain-free materials, like Pyrex, may be drilled after figuring is completed. Coverglasses of plate are pitched to both surfaces, an annulus of putty is formed around the site to be drilled, abrasive and water are introduced and the drilling accomplished as usual. After thoroughly cleaning the work, the pitch is softened with a radiant heater or water bath and the covers removed. All materials exhibiting strain in plane-polarized light and all untested pieces are most safely drilled before grinding by working one-third through from each face and filling the cuts with beeswax. When figuring is complete the wax is removed by immersing the work in cold water which is slowly (2 hrs.) heated to 145° F. After the disk has slowly and thoroughly cooled, the drilling is completed. The method of drilling and replacing the plug by cementing it with plaster is condemned on the ground that two strains are inevitable: When setting and hardening most plasters change dimension by large amounts—often .08 percent. During intervals of figuring the plaster is repeatedly dried and moistened. This involves a change in hydration of the calcium sulphate crystals near the surface of the plaster, with a possible dimensional change. It is recognized that many paraboloidal mirrors have been perforated, by following this

[10] Polaroid Corp., 168 Dartmouth St., Boston, Mass. It must be remembered that Polaroid is transparent to wavelengths over 7000 A.U. and cannot be used, therefore, for infra-red polarization.

criticized technique, but the improbability of attaining true precision by this method has been amply indicated to the writer by his past experiments, in which edge errors of large magnitude have been observed.

Grinding

This simple operation is fully treated elsewhere.[11] Important points are: The use of three disks, even if but one flat is desired, is strongly recommended. Wired glass, wood to which facets of ¼″ plate are pitched or flat vitrified building tile can be used for the additional disks. All surface blemishes should be removed completely with each abrasive—a matter much more difficult than is usually thought. The classic sequence should be rigidly maintained, as follows: 1 on 2, 2 on 1, 1 on 3, 3 on 1, 2 on 3, 3 on 2, 1 on 3, 3 on 1, 1 on 2, 2 on 1, 3 on 2 and 2 on 3. Evenly distributed pressure and smooth, quarter-diameter to third-diameter strokes appear to yield the most satisfactory results. Orford's method of wiping the outer five percent [12] of each disk free from abrasive two to six times during each wet is not essential but it is a practice which makes for good edges if employed with No. 280 and all finer abrasives. The "pencil" test is not recommended due to the danger of scratch formation.

Polishing

As with grinding, polishing can follow the established technic familiar to the telescope maker, with a few changes. Because no tools remain from grinding in most instances, due to the fact that the disks are ground upon each other, additional tools will be needed. They may be of glass, hardwood, metal or tile. If of wood, the tools should be used on top to prevent warping. For machine polishing the wood and metal tools are superior in that they can be drilled to receive the stud which moves them. Effort can thus be applied quite close to surface of the disk. All things considered, polishing probably is best done with iron or with iron-weighted wooden tools, using extremely hard pitch, HCF or cloth. Laps of .95 diameter are to be preferred, on top, run at a speed of 100 to 150″ per minute with a .3 diameter stroke and loaded to 0.5 to 1.0 lb. per in.^{2} It is well to polish all disks long enough to enable testing to be done, after which the best disk is used for cold pressing only while the other surfaces are being completely polished. When two disks are polished, the better is used for pressing during the time the last flat is being worked. In this way, extreme errors of any surface are avoided. It is perhaps good practice to limit polishing periods to one hour, after which the disk is cooled one hour while the lap used is pressed on another disk. The third disk can be worked in the interim with a freshly pressed lap.

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[11] Glazebrook—"Dictionary of Applied Physics," Vol. IV, pp. 336–339. "A. T. M.," pp. 76–81.

[12] "Lens Work for Amateurs", 1932, p. 164.

FIGURING

This tedious operation is expedited and precision is increased by the use of several tools of various sizes. In working a series of five 12¾″ flats, the writer used recently the following maple-backed pitch laps: 3—12″, 1—8″, 1—6″, 1—4″ and 2—2″. Three large laps were used in order that one might be pressed while another was drying and a third was polishing. The smaller laps were used to polish protuberant zones. One of the smallest was star-shaped so that abrasion would be at a maximum in the center, which was ½″ in diameter. Apart from other considerations, the low cost of wood makes it desirable. The above-mentioned eight pieces cost $2.20, whereas one large tool of glass would cost approximately twice as much as the set, if of the same thickness—one-eighth diameter. A disk of boiler plate, 12″ x 1½″, which was used as a weight, cost $3.70.

Although each surface presents an individual problem and every worker will obtain somewhat different results with any given method, a rough indication of how the above laps have been used will be given as a guide. General concavity can be corrected at the rate of one to three fringes per hour with the largest lap, used with .4 diameter strokes. General convexity readily yields to .25 diameter strokes, using the .6 diameter lap. A central hill is treated with the smallest lap, using strokes about .8 lap diameter. A central hollow is handled with the larger tools, which have been centrally pressed with small disks of the same diameter as the hollow. Raised zones respond readily to small laps worked over them, but a raised zone very close to the edge is difficult to remove, due to the tendency to turn the extreme edge quite badly. Many times, the well-pressed large tool, heavily weighted and run at .4 diameter stroke, will bring the disk to a slight but uniform convexity and obliterate the troublesome zone. This may fail, however, and the defect may persist after an otherwise satisfactory surface has been attained. In this case, the zone can be removed by a small lap in the shape of an annular segment used with a peripheral stroke. For hand-work, a guide may be fastened to the lap to hold it at the proper distance from the edge, as shown in Figure 2, at right.

Turned edge can be prevented in almost all cases by the use of laps surfaced with pure pitch which has been boiled for hours until it is so hard when cold that the thumb-nail can make no impression in five seconds of maximum pressure. Laps should be beveled at the edges and should not exceed .95 diameter in size. Such laps tend to scratch, especially with unwashed rouge and light pressure. This tendency can be minimized by the use of high pressure (.7 to 2.0 lb. per in.^{2}), by pressing a few minutes with full load before working and by observing great care in the parting or classifying of rouge. Turned edge can result from strange influences. At one time, the polishing of a flat was progressing satisfactorily—a perfect edge appearing at each hourly test. The sixth period, however, went poorly—the edge was one fringe turned. The eighth test indicated a turn of two fringes; so the work was stopped. The subsequent minute investigation found the trouble to arise from a 100-watt filament lamp which had been placed near the

work to replace a distant 200-watt bulb. The long infra-red radiation from the lamp had been absorbed by the water on the edge of the disk (water is opaque to the far infra-red), heating the edge, which rose in expanding and was polished away. Removal of the lamp caused the trouble to vanish, as did interposition of a large Aklo heat-absorbing filter.[13]

The necessity may arise that a previously perforated flat must be refigured. Since it is unwise to cement the plug in the disk with plaster, and since the plug may not be available, it is necessary to remove the center of

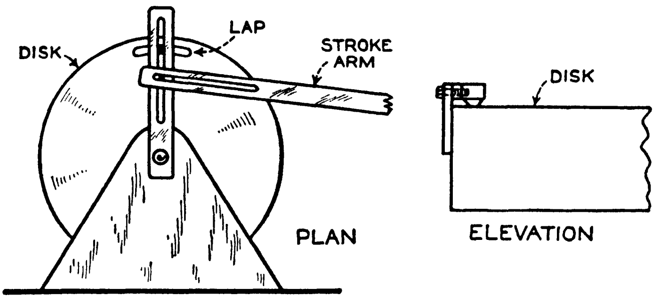


FIGURE 2

a lap, or to press it below the mean surface and proceed as usual. A 12″ flat with a 3″ hole was refigured in this manner. A 4″ area of a large lap was depressed with a weighted disk. The lap was then alternately pressed on a finished plane and worked on the perforated disk, using 3½″ strokes. Irregular errors of ± 0.2 wavelength were eliminated in five ten-minute periods.

When large laps are used, the piece being worked must be uniformly supported, especially if thin. Probably the cheapest material which is satisfactory is the resilient carpet backing, sold by home-furnishing establishments. It is obtainable in several thicknesses of which the thinnest is best for small, and the thickest for large flats. The barrel-head or the machine turn table should be free from general curvature.

At times it is advantageous to warm and soften laps. Glass-backed laps can be dipped in hot water, as is often done in spite of the fact that the glass warps while cooling, but wood-backed laps should be kept dry. It is convenient to employ a common electric radiant heater for this purpose and to heat from above, holding the reflector in one hand and turning the inverted lap with the other.

For long periods of cold pressing, the Lowers' method of using ten percent glycerin solution in water to carry rouge is excellent. Sufficient glycerin remains after the water has evaporated to insure freedom from sticking. Suitable guards should be placed to prevent the upper piece from sliding on

13 Corning Glass Works.

the lower. The glycerin should be removed by wiping with cloth before figuring is resumed. For short periods, pressing can be performed with a thoroughly dry lap, if it has been charged with rouge by previous use. It is the writer's experience that no sticking occurs in ten hours.

As an aid to machine figuring with small tools, a cardboard circle can replace the disk and a pencil can be inserted into the hollow stud which engages the lap. With this arrangement, a pattern will be drawn when the machine operates which will give approximately the mean resultant of the

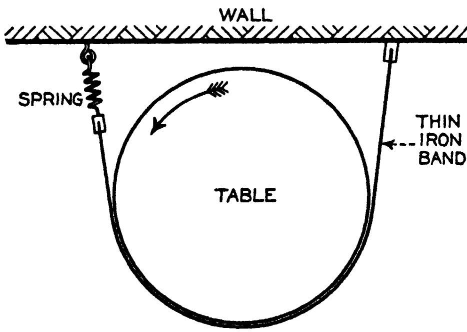


FIGURE 3

movements of the center of the lap for any stroke. These patterns can be very useful guides when reducing zones.

When using heavily-loaded tools which are run near the periphery of the work, a jerky movement is imparted to the turntable on which the work revolves. With even a well-constructed machine this will occur, due to slack in belts or chains, back lash in gears and spring in shafts. This jerking rotation, even when slight, tends to cause irregular surfaces, known as scrubs. The irregular motion can be prevented by the arrangement sketched in Figure 3.

To finish this section, the figuring of one flat will be briefly described. After completely polishing a disk, using a freshly-pressed large tool for one hour, cooling two hours and repeating with a freshly-pressed lap until finished, the disk showed the contour in Figure 4, at the left.

The edge, zone 1, was 1.0 fringe below mean plane, the second zone, 0.7 fringe above, the third 1.1 fringe below, the fourth 0.9 above and the center, 0.2 below. A 2″ star brought zone 4 to the level of 5 in 30 minutes, using a 2″ stroke. A 4″ lap, after 70 minutes of use with a 4″, center over center stroke, cut zones 5, 4 and 3 to a common plane. The small star was used again with a 4.5″ stroke, on zone two for two hours. This left the figure as in Figure 4, at right.

Zone 1, —.5 fringe; 2, +.5; 3, 0; 4, +.4; 5, 0 and 6, —.3. A 2″ normal tool, worked over zone 3 with a 4.5″ stroke for ten minutes reduced zones

2 and 4 to the level of 5. A newly-pressed, 12″ lap, fully loaded, was used with a straight, 5″ stroke for ten-minute periods, each followed by a one-hour cooling period. Seven periods were effective for bringing the surface to ± .2 fringe, except the edge, which was still —.5. The edge was finally brought to the mean level by using all three 12″ tools in rotation with 2″

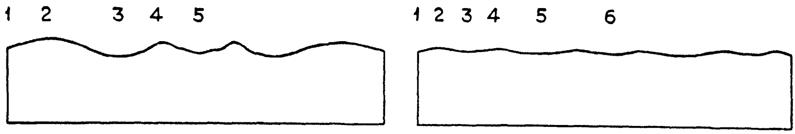


FIGURE 4

strokes for the usual ten-minute periods between cooling intervals of one hour or more each. The large tools were each faceted in a different manner, in order to avoid the introduction of zones, thus:

A 2″ facets between ⅝″ channels

B 1⅝″ " " ½″ "

C 1¼″ " " ⅜″ "

The tools were used in the following sequence: B, C, A; C, B, A; C, A, B; A, B, C; etc. Fifteen periods were necessary.

The above method is capable of yielding surfaces of high precision if the best disk is always used for pressing while the worse surfaces are being worked. This means that the disks will change places more or less frequently during figuring. Usually, one piece can be worked sufficiently plane over the area occupied by the largest lap early in the figuring stage, so that it can be used solely for pressing. When the remaining two are finished to the degree of precision necessary, they can be used for pressing the lap used to give the final figure to the edge zone of the first.

TESTING

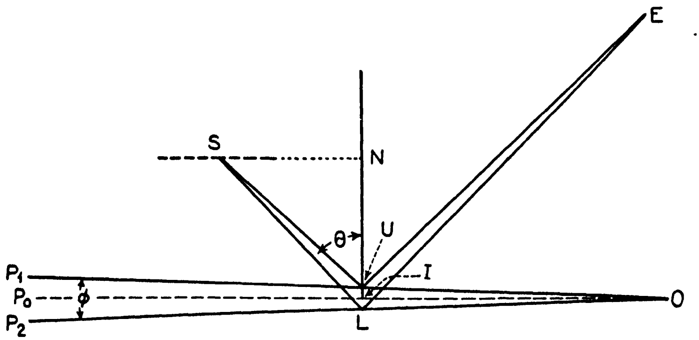
The worker is again referred to "A.T.M." for the general methods of testing plane surfaces.[14] Only hints and elaborations will be offered here. The Rayleigh water test is thoroughly practical if a few precautions are observed. Although glass loses relative density when immersed in water, the glass and container must be adequately supported. Vibration makes testing impossible; so the observation is best conducted after midnight. The liquid surface must be free from dust, etc., for such particles deform the surface locally. A thin coat of glycerin applied to the under surface of the cover glass prevents fogging and the addition of one percent gum arabic to the

[14] Pages 52–56.

water increases viscosity without causing a troublesome rise in refractive index, although the Tyndall effect does lower fringe contrast slightly. The container used should be 2″ greater in diameter than the flat, to avoid capillary edge effects. As the water and glass surfaces approach parallelism, the fringes separate rapidly. The thinner the water film above the flat, the brighter the fringe system will be. Unless the glass surface and the water surface are chemically clean, it is unwise to have a water film less than approximately .03″ in depth. It must be remembered that the curvature of the planet makes the water surface convex to the extent of .05 wavelength per foot. It is barely possible that precise experiments with large flats could demonstrate directly the effects of lunar and solar tidal pull on the surface, but such a factor need cause no alarm.

When testing flats in contact by interference,[15] a horizontal position is

[15] Explanation of fringe formation: P_1O and P_2O are surfaces perpendicular to the plane of the paper, separated by the small angular distance ϕ. From each of the many points in the light source S, two wave trains will reach the eye by reflection from P_1O and P_2O. It is obvious that, for finite values of ϕ, the paths SUE and SLE will be unequal and that for certain distances SN, the path differences will be $x\lambda + \frac{1}{2}\lambda$. Under each such situation, destructive interference will occur and the plane P_0O will appear dark. Halfway between each pair of dark spaces, maximum illumination will occur, for the two wave trains from this region will be in phase (path difference $x\lambda + \lambda$) and mutual reinforcement will result.



Condensed fringe equations: $UL = \dfrac{N\lambda}{2\cos\theta}$. (If N is a whole number, the point viewed will be dark, for wave trains change phase on reflection.) For normal incidence, $UL = \dfrac{N\lambda}{2}$

If r_n—radius of curvature of fringe of the n^{th} order
r_{n+s}—radius of curvature of fringe of the $n^{th} + s^{th}$ order
R—difference in radii of curvature of surfaces tested
θ—angle of incidence
d—$r_{n+s} - r_n$—distance between fringes considered
h—relative depth of curvature R
D—diameter of disk tested,

then, from the fundamental equation,

satisfactory for well-supported flats of great relative thickness, but perfect support is difficult and some pieces may be quite thin. Such disks are best tested vertically in a rack which supports the two at two points about 80° apart. The rack can be made of wood and so constructed that it can be filled while horizontal and later raised to the vertical for visual or photographic testing. This method is especially recommended for testing flats which are to be used in the vertical position. This rack is useful for determining the most stable diameter of a disk, since each flat can be rotated separately in relation to its mate. There is little danger of forming scratches, due to the fact that there is little or no interfacial pressure. For testing which requires precision of the order of 0.1 fringe, some additional precautions and equipment should be used. After the disks are cleaned with the bare hand and placed together, they should cool for at least an hour before an observation is attempted. With large, thick disks, stability of figure may not be reached for ten hours in exceptional cases. The testing room should not vary in

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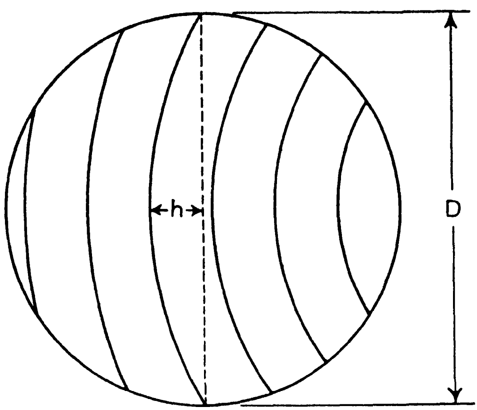

$$\lambda = \frac{(r^2_{n+s} - r^2_n)\cos\Theta}{8R}$$

the following equations can be derived:

$$R = \frac{d\cos\Theta\,(r_{n+s} + r_n)}{2\lambda} \qquad h = R \pm \frac{\sqrt{4R^2 - D^2}}{2}$$

The radius of curvature of any given fringe is given by,

$$r = \tfrac{1}{2}h + \frac{D^2}{8h}$$

From the above equations, it is apparent that the angle at which fringes are observed (Θ) is important, even for flats of small thickness. It is therefore important that straight fringes, especially between thick flats, be examined only vertically, *i.e.*, from the central normal to the surfaces, and from a great distance.

temperature at a rate greater than 0.2° F. per hour. The eye or the camera lens must be on the normal to the center of the disks, as must the light source. Two arrangements which fulfill this last condition are sketched in Figure 5.

Because of possible errors introduced by the inhomogeneity of the nearer disk, the poor figure of the diagonal plate, the errors of the outer surface of the nearer disk, the obliquity of extra-axial pencils and the distortion aberration of the camera lens, a control on these factors is needed. By accurately ruling a card with parallel lines and placing it between the flats be-

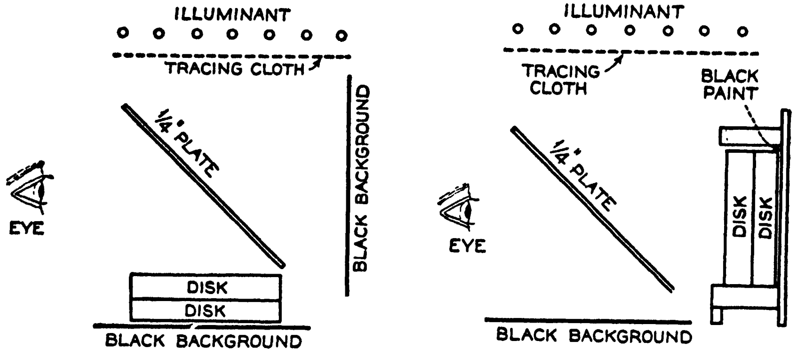

FIGURE 5

fore testing, such a control is obtained for all variables save pencil obliquity. If no lines appear or photograph other than straight at any point with any disk, the arrangement can be assumed to be free from error. The orientation of the nearer disk must be the same with and without the card and the fringes must occupy the same position as did the ruling. If distortion is noted, it will be necessary to determine direction and magnitude for each disk and to apply the proper correction. Corrections are difficult to apply visually, but photographic application is easily made. It is sufficient to make an exposure of the card in position and to compare the print with one from an exposure of the fringes. This procedure is repeated for each disk of the series. The exposures necessary must be found by experiment. For illumination, the writer uses a home-made gas tube lamp of grid form, one meter square, filled with argon and mercury vapor and operating at 10,000 volts and 1.1 ma. per meter of tube. With Eastman process plates, the light 6′ and the lens 3′ from the fringes, exposures average 40 seconds at $f/1.8$. When testing disks of the same diameter which are mutually centered, a turned edge is invisible unless it is gross and wide. In order to examine critically the edge of a disk, it must be on the bottom and the upper disk must be offset until the edge of the lower disk is clearly visible. See Figure 6.

To the above precautions, the following must be added, for no oblique

incidence correction has been considered and it is obvious that a fringe cannot be photographed from the normal to more than one point at once:

1. The lens should be at least ten disk diameters from the fringes.
2. When first placed together, the disks should be firmly pressed at the center of the top member.

FIGURE 6

The larger plane is free from edge defect, as close inspection of the true edge (the circle of minimum radius) will show. Beyond the edge, however, reflection artifacts give a series of spurious fringes which the photographic emulsion records. They are visually quite inconspicuous.

3. The flats should press horizontally for several hours before photographs are made.
4. Only diametral fringes should be used for tests.[16]

When testing a flat with a spherical mirror, the greatest accuracy can be attained only if the sphere is of moderate aperture ratio. That of $f/8$ is satisfactory and $f/10$ is better. Due to the fact that the writer dislikes this

[16] When observing a diametral fringe between true planes from the central normal, the error introduced by the obliquity of peripheral pencils is

$$E = t\left(\frac{\sqrt{d^2 + r^2}}{d} - 1\right)$$

where d=lens to fringe distance
r=radius of disk
t=thickness of air film

For 12½" flats viewed from 10′, the error equals $0.0015t$. Since t is a function of the order of the fringe observed, which cannot be determined easily by the amateur, it is necessary to rely upon approximate values.

The writer has measured t in many instances with a crude spectroscope and has found values ranging from 10 to 40 wavelengths for small flats quite loosely fitted, to 0.8 to 5 waves for large disks after ten hours of pressing.

Assuming that $t = 10$ W.L. $\pm$ and that the four above conditions apply, the oblique error should not exceed approximately 0.02 wave.

method, which yielded results of low precision in his hands some years ago, he has little comment to make regarding it.

Some glasses which are but slightly strained react quite unpredictably to thermal change. When first testing by interference it is advisable to leave each pair in the testing rack for several hours, noting the fringe pattern at zero time and after one-half, one, two and ten hours. In this way, the cooling characteristics of each disk may be observed.

Special Applications

Diagonals: These are made rectangular or elliptical, according to the desire of the maker. A rectangle with sides of 1:1.413 ratio obstructs light to the same extent as does an equivalent 90° prism. The elliptical type ob-

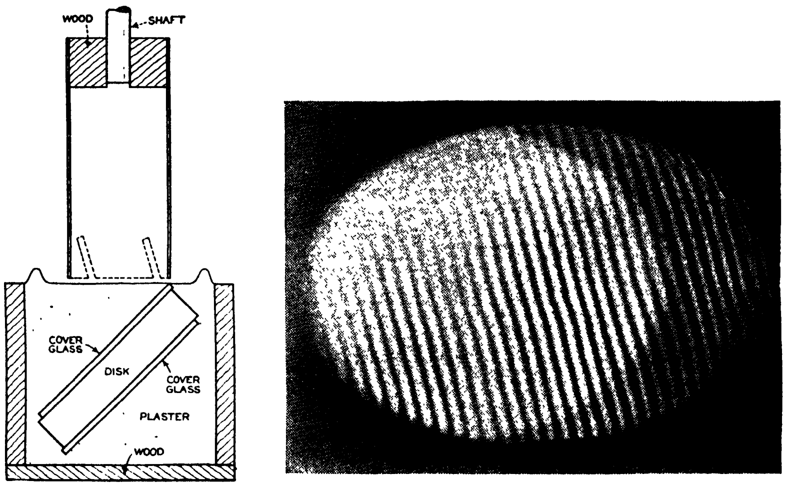

Figure 7

structs only .785 as much light, but cutting is more difficult. A rectangular form is often made by sawing from a previously-figured disk. With strain-free material, this is satisfactory. Strap iron is used in a power hacksaw and fed with Carborundum and water. If, in spite of the previous objections to the use of plaster, it is desired to work a rectangular flat in the center of a circular block filled out with scrap glass, as described in "A.T.M.," [17] Hydrocal A-11, manufactured by the U. S. Gypsum Co., may be tried. The setting expansion of this plaster is only .0003. Much better results can be secured by balsaming the work and riders to a cast-iron flat and finishing.[18]

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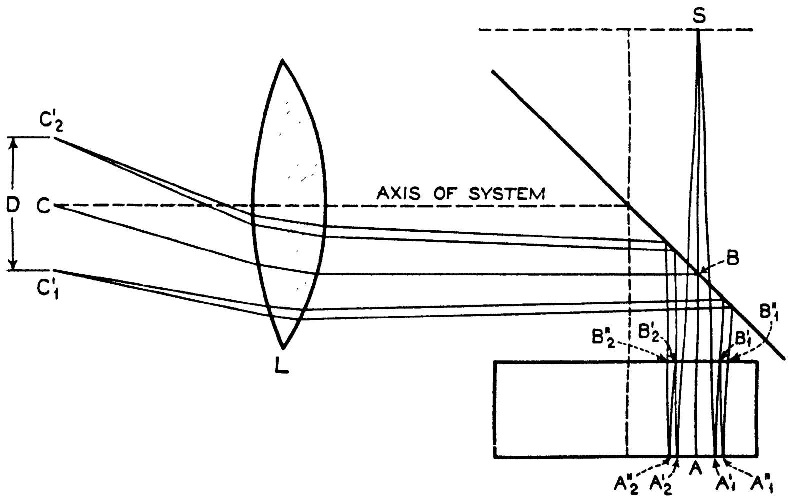
[17] Page 54.
[18] Ord. Dept., U. S. A., Doc. 2037.

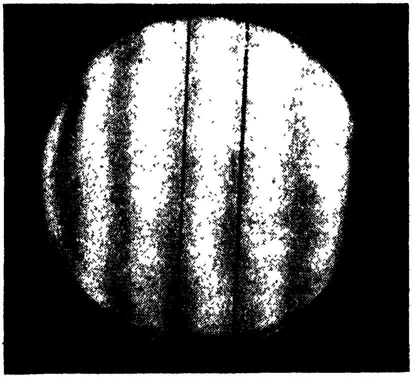
Elliptical diagonals can be cut by pitching to the circular blank two cover-glasses, casting the combination at 45° in a plaster mold and drilling the entire cast with a brass tube of suitable diameter. (See Figure 7; to the right is shown a flat cut in this manner. Note turned edge.) This can be done after figuring without greatly deforming the edge, if strain-free glass is used. With other glasses, the drilling is best done before polishing. The drilled disk can then be affixed to a cast-iron flat and the work completed after filling the moat with beeswax.

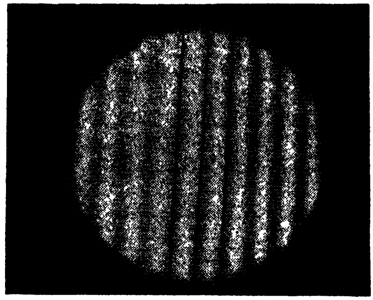
Plane-parallels: Under this head may be listed, in approximate order of precision required, hemacytometer cover glasses, light filters for photography, sextant mirrors, echelon grating planes and interferometer plates. The necessary surface accuracy varies from ± 1 wave-length for the first, to ±.05 for the last. Since these objects are relatively small and thin, they are worked while cemented to accurately plane iron disks. When one surface is finished, this surface is placed in optical contact with the iron, the edges are sealed with wax and the exposed surface is ground and polished, close attention being paid to the total thickness of the block, which must be constant for all diameters, ±.01 mm. The above method is too inaccurate to serve for testing parallelism of grating and interferometer parts and an optical method is used. This method applies the principles of Haidinger's fringes.[19]

[19] The interference phenomenon to which Haidinger's fringes owe their existence occurs between the weak reflected wave trains ($B'C'$) and the extremely feeble, trebly-reflected trains ($B''C'$). Therefore, when the paths differ by $x\lambda+\lambda$ and maximum brightness occurs, the illumination added by the second train is very slight. This accounts for the low contrast of the ring system.



If the testing arrangement of Figure 5, at left, is used and the plane-parallel under test occupies the position of the two flats in the figure, a faint ring system can be observed by accommodating the eye for infinity or by using a small telescope, previously focussed for distant objects. If, when the flat



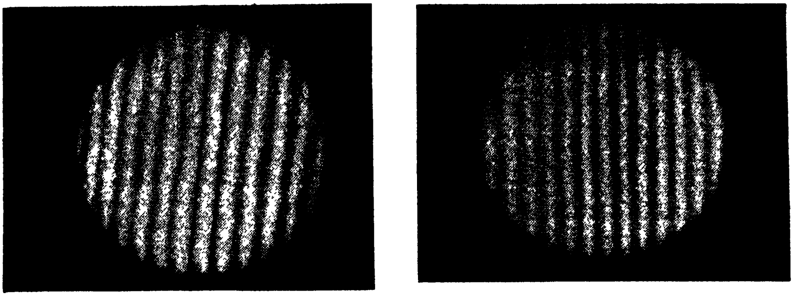


These and other similar groups of two nearby are fringe photographs of flats made by the author, who writes, "The mates of each pair are of identical figure, having been worked on the same lap for the same periods during a minimum of 50 hours each. Each forms the same fringe pattern, as does its mate when in contact with a third plane. The obliquity error in no case exceeds .007 wave. Illumination was by the following spectral lines of the arc: mercury, 4046 a.u.; argon, 4013, 4072 and 4104 a.u. Weighted mean wave-length, 4060 a.u." The one shown at the left, is a 12½". Fringe separation, on negative, 13.7 mm. Max. deviation, 0.146 fringe or 0.073 wave—each disk 0.037 wave. The one at right: Sep. 6.0. Error, 0.13 fringe, 0.06 wave, or 0.03 wave for each flat. The dark lines were inked on the photographs by the author.

is moved in a horizontal plane, the ring system neither contracts nor expands (the central ring only should be observed), it is an indication that the surfaces are parallel. If the plane-parallel under test does not have parallel faces, the magnitude of the error can be determined by moving the plate a known distance and counting the number of rings which form or vanish at the center of the system. The rings contract as the plate is moved towards the thinner section. Obviously, the plate should be moved along many diameters and that one chosen for test which causes the greatest number of rings to vanish. If 20 fringes were lost in 10 cm. of travel, the higher

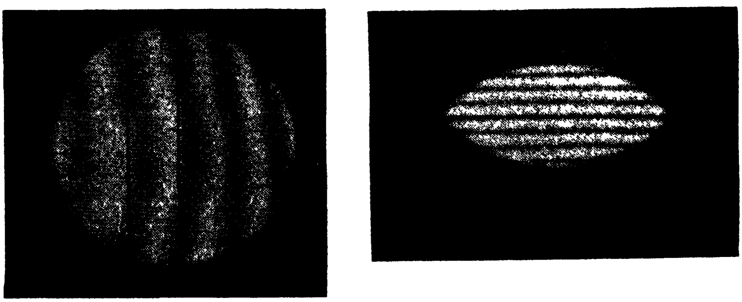
In the figure, a ray SA', from every point in the illuminant, being parallel to a ray from each other point, is refracted by L to C, the axial focal point. Other rays, however, not striking the plane-parallel normally, proceed from S to A', whence a small fraction returns to B', is largely carried to C', leaving a fraction to be reflected at B' and A'', which also reaches C'. The same process occurs around point A, forming a cone, the wave trains of the components of which mutually interfere at the circle $C'_1C'_2$, which has a diameter D. D corresponds to the circle $A'_1A'_2$, the diameter of which controls the phase relationship of the B' and B'' rays. For every point S, a similar behavior occurs and, because the determining factors are only the radii AA'_2 for any one example, the rings from identical radii from various points coincide, and a concentric system is formed on C.

point would be 10 wavelengths above the lower, relative to the opposite face, and the plate would be out of parallelism by one wavelength per cm.,



Left: Diam. 12½″. Fringe separation, 4.9 mm. Max. deviation, 0.8 mm. or 0.081 wave, or each disk, 0.04 wave. Right: Diam. 12″. Sep. 4.3. Error 1.0, or .23 fringe, .13 wave, or .07 per surface.

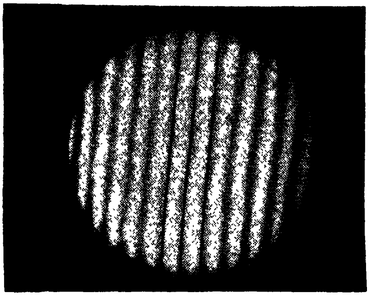
for thickness equals $\frac{nd}{2\mu \quad \cos\Theta}$ and this becomes, for vertical incidence and the central ring, $\frac{n\lambda}{2\mu}$. Prismatic error then equals $f/2$ waves, where $f =$ number of fringes disappearing, or change in n. The fringes lack con-

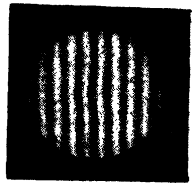


Left: An 8″ x 1¼″ plane on an unfinished 8″ x ¼″ disk which is ⅛ wave convex. Fringes correctly photographed. Right: The same 8″ disks improperly photographed to show influence of angle of incidence—all fringe photographs taken at an angle should be viewed with suspicion.

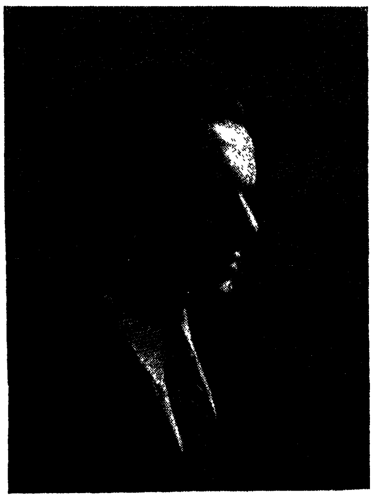
trast and are difficult to see, but the phenomenon can be intensified by very lightly silvering both faces.[20]

[20] Wood—"Physical Optics," 3rd Ed., p. 209.





Left: 12¼". Separation 4.7 mm. Error, 1.0 mm., or .21 fringe, .1 wave, or .05 wave per surface. Right: 6½". Sep. 3.4 mm. Max error, 0.5 mm., .147 fringe, .073 wave, or each disk, .036 wave.



The Author

By piecing together some fragments already known about him, with a few facts obtained by third degree methods, a "Who's Who in Amateurdom" item has been constructed: Mr. Selby is chief chemist for a California food products plant. He has also been a truck driver, and a dishwasher in a lumber camp. His avocation is mathematical optics and he states that he dislikes the work of making optical systems, and that the only pleasures are to be found in computation and use. He has computed and constructed for his own use an apochromatic triplet telescope objective, a number of astronomical oculars, two anastigmatic photographic objectives and such microscope parts as a Bertrand lens, a wide aperture achromatic condenser and a 12 mm. achromatic objective. He has made a big paraboloid, two f/1 spheres and about 50 flats. He dislikes to write letters.—Ed.

ACCURACY

For many applications, the "quarter-wave" limit of accuracy is sufficient. This applies to photographic filters, diagonals, prism faces and the plane surfaces of objectives. For interferometer planes $\pm .05$ wave is none too flat[21] and surfaces should be parallel $\pm .1$ wave per inch. For coelostat mirrors and for the outside reflecting planes of telescopes, such as the Gerrish, the accepted limit of error is $\pm .1$ wave. Freedom from zonal and periodic errors is assumed. The plane mirrors which are used in testing paraboloids and completed telescopes at their foci must be quite accurately plane. The accuracy of surface theoretically necessary differs with the application, but it is safe to assume that any tolerance less rigid than ± 0.1 wavelength is too liberal.

The suggestions offered in the above short article are admittedly sketchy and perhaps incomplete and the methods offered will be considered incorrect by some. These criticisms are to be expected, for the subject of flats can be thoroughly treated only in a large volume written by a true master of the art, and the writer could by no means arrogate to himself this title.

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[21] Michelson—"Studies in Optics," 1927.

Notes on the Optical Testing of Aspheric Surfaces

By Horace H. Selby

The amateur telescope maker has at his command methods of testing spheres, paraboloids, hyperboloids, ellipsoids and planes which are amply precise and thoroughly satisfactory. Many such methods, however, depend on visual acuity, ocular contrast sensibility and personal judgment of geometric forms.

These apparently new test methods are different, in that they give results in terms of measurement and are, therefore, in some cases preferable to

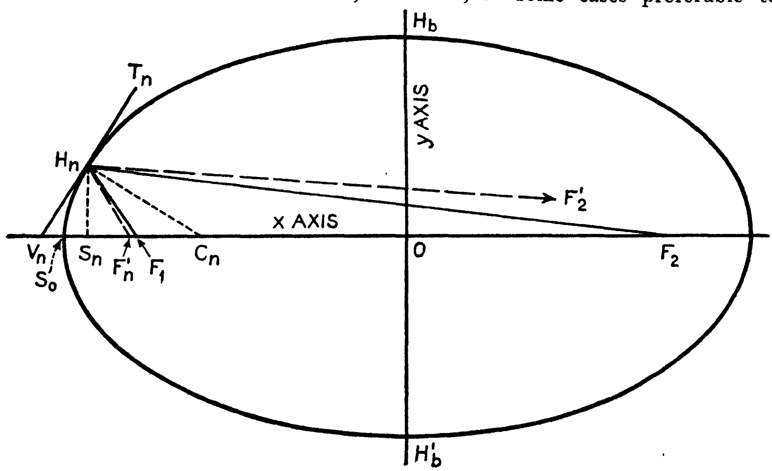


Figure 1
Ellipsoid.

other methods. No crying need for these methods exists—they are not necessary for most work. They are published here as possible aids to the advanced amateur in solving specialized problems, and as "different" methods by which other methods may be checked by the hobbyist whose earthly joys are mathematics and optical experimentation.

The ellipsoid: The ellipsoid is, by definition, the conic of revolution which will bring all rays emanating from a point to a focus at another point. The secondary mirror of a Gregorian should have an ellipsoidal figure. The common methods of testing ellipsoidal surfaces (Kirkham's, Hindle's and Foucault's) yield results of high precision and are satisfactory. The criterion of perfection is the degree to which the surface approaches apparent flatness under the knife-edge, or the degree to which the bands approach straightness and parallelism if the tests of Jentsch or Ronchi are used.

It seems, however, that many experimenters find the judgment of flatness and straightness difficult and prefer a method of measurement. Also, instances may be found in which a definite amount of under- or over-correction is desired. Such a method is outlined below, with the usual mathematical development. The only variables considered are the easily-measured distances, P, P', r_n and D, the distance of the source.

In Figure 1, $H_bSoH'_b$ is an ellipse symmetrically described about o, the intersection of the x axis with the y axis. F_1 and F_2 are the foci. V_nT_n is the tangent at H_n. H_nS_n is the radius of the H_n zone and is identical with r_n. As is usual in the description of compound telescopes, SoF_1 is called P, SoF_2 is termed P'.

With the source at F_2 and the knife-edge at F_1, or vice versa, the surface appears flat if perfect. If, however, the source is moved to F'_2, the surface appears to be changed and the knife must be moved to a different position, F'_n, in order to "focus" each zone, H_n, of the mirror. Each zone requires a setting different from every other and the object of this paper is to develop simple formulae in P, P' and r_n by which this focal shift can be determined. This shift, $\Delta F'$, will usually be the focal difference between two zones, one near the center, the other near the edge. With special equipment, the center and the extreme edge can be used, but there is no advantage in this procedure.

In the following, the distance of the light source is D, which equals SoF'_2, the distance, axially, from the surface tested.

Equation of curve: $\dfrac{x^2}{a^2} + \dfrac{y^2}{b^2} = 1 \qquad y = \dfrac{b\sqrt{a^2 - x^2}}{a} \qquad x = \dfrac{a\sqrt{b^2 - y^2}}{b}$

Where $a = OS_o \quad b = OH_b \quad x = OS_n \quad y = HnSn \quad \dfrac{dy}{dx} = \dfrac{xb}{a\sqrt{a^2 - x^2}}$

In terms of P, P' and x, $a = \dfrac{P' + P}{2} \quad b = \sqrt{P'P}$

$$x = \frac{(P' + P)\sqrt{P'P - r^2}}{2\sqrt{P'P}} \qquad \frac{dy}{dx} = \frac{2\sqrt{P'P}\,\sqrt{P'P - r^2}}{r(P' + P)}$$

In the figure, $Hn\,Cn$ is $\perp Vn\,Tn \quad \therefore \angle Cn\,Hn\,F_2 = \angle Cn\,Hn\,F_1$

Also $\angle Sn\,Hn\,Cn = \angle Hn\,Vn\,Sn \quad \therefore \angle Sn\,Hn\,F'n = 2\,Hn\,Vn\,Sn - Sn\,Hn\,F'_2$

$$\text{then } \tan Sn\,Hn\,F'n = \frac{2\tan Hn\,Vn\,Sn - \tan Sn\,Hn\,F'_2 + \tan^2 Hn\,Vn\,Sn \dfrac{\tan Sn\,Hn\,F'_2}{Hn\,F'_2}}{1 - \tan^2 Hn\,Vn\,Sn + 2\tan Hn\,Vn\,Sn\,\tan Sn}$$

but $\tan Hn\,Vn\,Sn = \dfrac{dy}{dx} = \dfrac{2\sqrt{P'P}\,\sqrt{P'P - r^2}}{r(P' + P)}$ and $\tan Sn\,Hn\,F'_2 = \dfrac{D - So\,Sn}{r}$, or

$$\tan Sn\,Hn\,F'_2 = \frac{2D\sqrt{P'P} - (P'+P)\left(\sqrt{P'P} - \sqrt{P'P - r^2}\right)}{2r\sqrt{P'P}}$$

and, since $\tan Sn\,Hn\,F'n = \dfrac{Sn\,F'n}{r}$,

$$Sn\,F'n = \frac{r^2(P'+P)[8(\sqrt{P'P})^2\sqrt{P'P-r^2} - 2D\sqrt{P'P}(P'+P) + \sqrt{P'P}(P'-P)^2 - \sqrt{P'P-r^2}(P'+P)^2] + 4(\sqrt{P'P})^2(\sqrt{P'P-r^2})^2}{2\sqrt{P'P}\{(P'+P)^2[r^2 - 2\sqrt{P'P}\sqrt{P'P-r^2} + 2(\sqrt{P'P-r^2})^2] + 4\sqrt{P'P}\sqrt{P'P-r^2}\,[D(P'+P) - \sqrt{P'P}\sqrt{P'P-r^2}]\}\,[2D\sqrt{P'P} - \sqrt{P'P}(P'+P) + \sqrt{P'P-r^2}\,(P'+P)]}$$

$$So\,Sn = OSo - OSn = \frac{P'+P}{2} - \frac{(P'+P)\sqrt{P'P-r^2}}{2\sqrt{P'P}}$$

$$= \frac{(P'+P)(\sqrt{P'P} - \sqrt{P'P-r^2})}{2\sqrt{P'P}}$$

Then $\triangle F'$ (from center to edge) $= P - Sn\,F'n - So\,Sn$
and $\triangle F'$ (from zone A to zone B) $= S_B\,F'_B + S_O\,S_B - S_A\,F'_A - S_O\,S_A$
where A is the inner, and B the outer zone.

Although the formulae are lengthy and appear to be complex, application requires nothing more than arithmetic and the average example can be applied in an hour or two, once the distances P, P', r and D are known.

The ellipsoid can be tested at "center of curvature," also, in which case, the lamp and knife-edge will move together from Cn toward So to Co through the distance ΔC, which equals $OCo - OCn$.

In all cases, $$\Delta C = \frac{(P'-P)^2\left(\sqrt{P'P} - \sqrt{P'P-r^2}\right)}{2\sqrt{P'P}\,(P'+P)}$$

Testing the paraboloid on near objects: At times it may be desirable to test a telescope mirror or a complete telescope on a light source not situate at either center of curvature or at infinity. The formulae developed below make such testing simple.

In Figure 2, $VnTn$ is tangent to the curve at Hn. $HnCn$ is normal to the tangent. ∞HnF is the normal ray path. $F_2HnF'n$ is the new ray path.

Let $Sn\,Hn = rn$, the mean radius of zone n, $= y$.
$So\,F = P$, the equivalent focal length.
$Hn\,Cn = Rn$, the radius of curvature of zone n.
$So\,F_2 = D$, the axial distance of the source from the mirror.
x, y the coordinates of the point Hn.

Equation of curve: $y^2 = 4\,Px \quad \dfrac{dy}{dx} = \sqrt{P/x} = \tan Hn\,Vn\,Sn = \dfrac{r}{Vn\,Sn}$

then $\tan Hn\,Cn\,Sn = \sqrt{x/P} = \dfrac{r}{Sn\,Cn}$ and $Sn\,Cn = \dfrac{r\sqrt{P}}{\sqrt{x}}$

but $x = \dfrac{r^2}{4\,P}$ $\therefore$ $Sn\,Cn = 2\,P$ and $So\,Co = 2\,P$

Also, since $So\,Sn = x = \dfrac{r^2}{4\,P}$, $Co\,Cn = \Delta C = \dfrac{r^2}{4P}$, which is the usual formula giving the movement of the knife-edge and source together. Here it is interesting to note that the mirror depth is equal to the knife-edge travel.

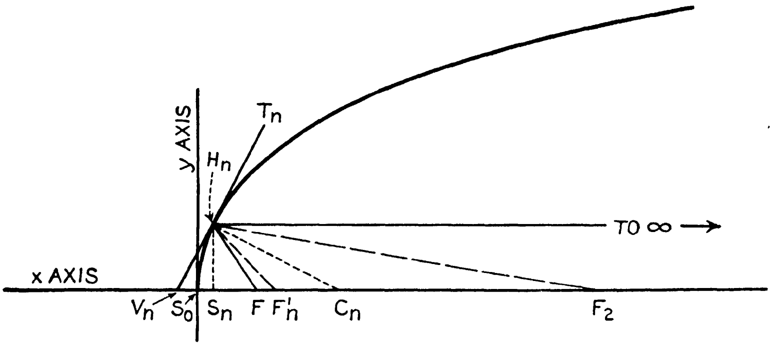


FIGURE 2
Paraboloid.

If the source is at infinity, the true paraboloid will appear to be flat and evenly illuminated if observed from F. When the source is moved toward the mirror, the apparent figure changes and the blade must be moved to a new position for each zone. The difference of position for two zones is denoted ΔF and can be determined by use of the formula derived below:

$$\tan Sn\,Hn\,F = \frac{Sn\,F}{r} = \frac{4\,P^2 - r^2}{4\,Pr}$$

$$\tan FHn\,F'n = \frac{r}{D - So\,Sn} = \frac{4\,Pr}{4\,DP - r^2}$$

$$\therefore \tan Sn\,Hn\,F'n = \tan (Sn\,Hn\,F + FHn\,F'n) =$$

$$\frac{Sn\,F'n}{r} = \frac{4\,P(4\,DP^2 - Dr^2 + 3\,Pr^2) + r^4}{16\,P^2\,r(D - P)}$$

then $Sn\,F'n = \dfrac{4\,P(4\,DP^2 - Dr^2 + 3\,Pr^2) + r^4}{16\,P^2\,(D - P)}$

and $So\,F'n = \dfrac{16\,DP^3 + 8\,P^2\,r^2 + r^4}{16\,P^2\,(D - P)}$

when $r = o$, $So\,F'n = So\,F'o = \dfrac{DP}{D-P}$

$\therefore\ \triangle F'$ (between center and edge) $= So\,F'n - So\,F'o =$
$\dfrac{r^2(8\,P^2 + r^2)}{16\,P^2(D-P)}$

Unless special equipment is used, however, the center is not available, being blocked by a prism or by a diagonal. It then becomes necessary to determine the focal difference of two extra-axial zones. Where A is the outer, and B, the inner zone, the equation becomes:

$$\triangle F' \text{ (between zones A and B)} = \frac{r^2_A(8\,P^2 + r^2_A) - r^2_B(8\,P^2 + r^2_B)}{16\,P^2(D-P)}$$

Quantitative test of hyperboloidal mirrors: Several experimenters have recommended testing hyperboloids from the back, among them, Ellison and the Lowers. The test has been but a visual examination for smoothness of figure, however, and measurement of zonal foci have not been attempted.

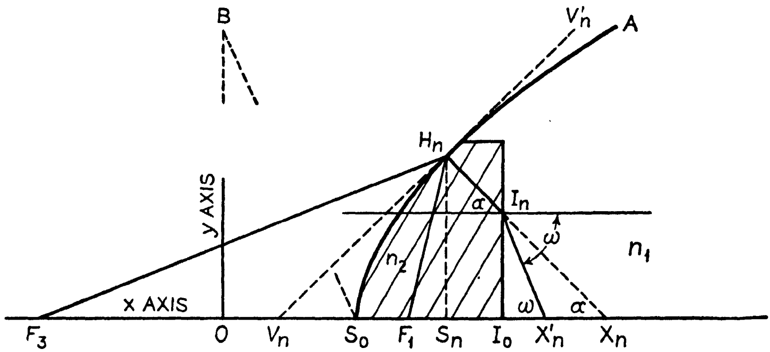


FIGURE 3
Hyperboloid.

In 1935, Robert Russell, in unpublished work, attempted to make such testing practical. It is to Russell that the writer is indebted for the idea of developing a quantitative test. Such an idea had never occurred to him before he was allowed to criticize Russell's work.

In Figure 3, $VnV'n$ is the tangent to the hyperbola $SoHnA$ at Hn. $HnXn$ is the normal. $SoIo$ is the axial thickness of the denser medium. $HnSn$ is the perpendicular to the axis from Hn. As is usual with Cassegrain telescopes, $F_3So = P'$ and $SoF_1 = P$.

Let $Hn\,Sn = r_n$, the radius of zone n, $= y$
$So\,Io = T$, the thickness, axially of glass (or of glass and liquid, as in the King Test.)

$$
\begin{aligned}
&O\,So &&= a = \frac{P' - P}{2}\\
&O\,B &&= b = \sqrt{P'\,P}\\
&x, y &&= \text{the coordinates of } Hn
\end{aligned}
$$

Equation of curve: $\frac{x^2}{a^2} - \frac{y^2}{b^2} = 1$

$$y = \frac{b\sqrt{x^2 - a^2}}{a} \qquad \frac{dy}{dx} = \frac{xb}{a\sqrt{x^2 - a^2}}$$

$$x = O\,Sn = \frac{(P' - P)\sqrt{P'\,P + r^2}}{2\,\sqrt{P'\,P}} \qquad \frac{dy}{dx} = tan\ Hn\ Vn\ Sn =$$

$$\frac{r}{Vn\ Sn} = \frac{2\sqrt{P'\,P}\sqrt{P'\,P + r^2}}{r(P' - P)}$$

$$\therefore tan\ Hn\ Xn\ Sn = \frac{r(P' - P)}{2\sqrt{P'\,P}\sqrt{P'\,P + r^2}}.$$

Since $O\,Sn = \frac{(P' - P)\sqrt{P'\,P + r^2}}{2\sqrt{P'\,P}}$,

$O\,So = \frac{P' - P}{2}$ and $Sn\ Xn = \frac{2\sqrt{P'\,P}\sqrt{P'\,P + r^2}}{(P' - P)}$

$$\therefore So\ Sn = \frac{(P' - P)(\sqrt{P'\,P + r^2} - \sqrt{P'\,P})}{2\sqrt{P'\,P}}$$

$So\ Xn = So\ Sn - Sn\ Xn =$

$$\frac{(P' - P)^2(\sqrt{P'\,P + r^2} - \sqrt{P'\,P}) + 4\,P'\,P\,\sqrt{P'\,P + r^2}}{2\sqrt{P'\,P}(P' - P)}$$

When $r = O$, $So\ Xn = So\ Xo = \frac{2\,P'\,P}{P' - P}$

$\therefore \Delta R$ (for zero thickness) $= So\ Xn - So\ Xo =$

$$\frac{(P' + P)^2(\sqrt{P'\,P + r^2} - \sqrt{P'\,P})}{2\sqrt{P'\,P}\,(P' - P)}$$

Using the above as a basis, ΔR can be calculated for hyperboloids of known thickness and refractive index (n_2) as follows:

$$sin\ \omega = \frac{n_2\,r}{\sqrt{r^2 + \overline{Sn\ Xn}^2}},\quad In\ Io = \frac{r(So\ Xn - T)}{Sn\ Xn},$$

$$Io\ X'n = \frac{(So\ Xn - T)\sqrt{r^2 + \overline{Sn\ Xn}^2 - n_2^2\,r^2}}{n_2\,Sn\ Xn}$$

and $Io\ X'o = \frac{So\ Xo - T}{n_2}$

Then $\Delta R = Io\,X'n - Io\,X'o =$

$$\frac{[(So\,Xn - T)\sqrt{r^2 + Sn\,Xn^2 - n_2^2\,r^2}\,] - Sn\,Xn\,(So\,Xo - T)}{n_2\,Sn\,Xn}$$

Substituting and rearranging,

$$\Delta R = \frac{[(P' + P)^2\sqrt{P'\,P + r^2} - (P' - P)\sqrt{P'\,P}(2T + P' - P)]}{}$$

$$\frac{\sqrt{r^2[(P' + P)^2 - n_2^2(P' - P)^2] + 4\,\overline{P'\,P}^2}}{4n_2\,P'\,P\,(P' - P)\sqrt{P'\,P + r^2}}$$

$$-4\,P'\,\underline{P\sqrt{P'\,P + r^2}\,(2\,P'\,P - TP' + T\,P)}$$

How to Make Rouge

By Horace H. Selby

There are but three iron oxides which interest us—ferrous oxide, FeO, which is an intermediate oxidizing in air to ferric oxide, Fe_2O_3, which is red rouge. Fe_2O_3 can be changed to ferrous ferrite, $FeOFe_2O_3$, which is black "rouge."

Next, common rouge and how it is made:

a. Ferrous sulfate, copperas, $FeSO_4$, can be ignited in air to form ferric oxide. Product bad. Reaction:

$$4FeSO_4 + O_2 \rightarrow 2Fe_2O_3 + 4SO_3$$

b. Ferrous hydroxide, $Fe(OH)_2$, can be made from a filtered solution of ferrous sulfate, $FeSO_4$, and ammonium hydroxide, ammonia water, NH_4OH. The $Fe(OH)_2$ is filtered off, washed, dried and ignited as above. Product good. Reactions:

$$FeSO_4 + 2NH_4OH \rightarrow Fe(OH)_2 + (NH_4)_2SO_4$$
$$4Fe(OH)_2 + O_2 \rightarrow 2Fe_2O_3 + 4H_2O$$

c. Ferrous oxalate, FeC_2O_4, can be made from ferrous sulfate and oxalic acid, $H_2C_2O_4$. The two solutions are filtered and mixed hot. The precipitated yellow oxalate is washed, dried, and ignited as above. Product good. Reactions:

$$FeSO_4 + H_2C_2O_4 \rightarrow FeC_2O_4 + H_2SO_4$$
$$4FeC_2O_4 + 3O_2 \rightarrow 2Fe_2O_3 + 8CO_2$$

If ignited out of contact with air, ferrous oxide, FeO, results:

$$FeC_2O_4 \rightarrow FeO + CO_2 + CO$$

There are other methods, but they are possible only in a laboratory.

Now for ferrous ferrite, $FeOFe_2O_3$, black "rouge." This can be made by heating the Fe_2O_3, obtained as above, in an atmosphere of hydrogen or carbon monoxide, H_2 or CO.

Reaction:

$$3Fe_2O_3 + H_2 \rightarrow 2(FeOFe_2O_3) + H_2O$$
$$\text{or} \quad 3Fe_2O_3 + CO \rightarrow 2(FeOFe_2O_3) + CO_2$$

At 400° C. the product is soft, polishes slowly, leaves no sleeks with a soft lap and has a density of 4.86.

At high temperatures—1000°C.—it is harder, polishes more quickly, has density of 5.05.

Both are octahedral crystals, black and magnetic. This is the most stable iron oxide.

Now to return to the ferrous oxide, FeO, which is unstable in air. If it is heated to 1570° C. (approx.) immediately after manufacture, in contact with oxygen, it will melt and upon cooling, will form red rhombohedral plates of Fe_2O_3, rouge, which have a density of 5.19. This must be powdered.

In the first methods of making red rouge, Fe_2O_3, low ignition temperatures give bright, fine rouges which powder well and polish slowly. High temperatures (600–1100° C.) yield dark, dense, coarser rouges which are less friable but which polish faster. Such products are called, not rouge, but crocus and are used in the foundry for metal polishing.

[EDITOR'S NOTE: As the attentive reader will have noted, there are several points in the note on the opposite page at which additional instructions might have been inserted. For example, just how to "ignite out of contact with air," also how to handle the low and high ignition temperatures mentioned.

Accordingly, it was suggested to the author, who is a chemist, that he expand somewhat on these points. His reply was that most of "those who do not find it possible to make rouge from the data given would only bungle the job if told how to do it. Probably," he continued, "a certain background of laboratory experience is needed, so why not head the story 'For those chem. hounds alone who want to experiment with rouge making, we give this dope. For others, if it isn't clear, better not try—it is cheaper to buy rouge, anyway.' "

No doubt this is true, but it still is not entirely in accordance with the nature of human nature. Past editorial experience with the human race in general indicates that many will not take such a no for answer, especially where the situation contains something of a challenge. Hence the likelihood was foreseen that, down through future years, many inquiries would be addressed to author and publisher, each asking for "full details" on rouge making laboratory technic, and so the matter was referred to Dr. S. H. Sheib of Richmond, another chemist-telescope maker, for opinion. He replied, "I think Selby is exactly right. Give them warning that rouge making is not as easy as it looks and that, unless they have had a year of lab. work, preferably two, they had better not tackle it. If then they insist on doing it, let them prepare for it by studying in the lab. This sort of work must be done in a properly equipped laboratory. Take, for example, igniting out of contact with air. That means heating in a metal bomb with a tightly fitting screw top; or else, if every trace of air must be removed, some sort of refractory container provided with air inlet and outlet tube by means of which the air may be swept out by passing some inert gas through the container. It is not a job for a beginner. This thing isn't like silvering, for which one requires only a pan and a couple of tumblers. Here you need pretty complete and expensive equipment—gas generators, combustion furnace, etc., and a fundamental working knowledge of chemistry."

Doubtless by this time some are sure they want to try to make rouge. Hence, if you are one of these, good luck, and may no hard-hearted cynic label your product road ballast.]

Small Lens Wrinkles

By Russell W. Porter
Pasadena, California

Judging from the letters I receive from men who have made their mirrors, and are now contemplating or actually making their eyepieces, it would seem that an increased interest has sprung up among amateurs who desire to complete their entire telescopes with their own hands. I have for years urged mirror makers to try their hand at small lens making, telling them that the difficulties are no greater, and that the fun is just as great. I have picked

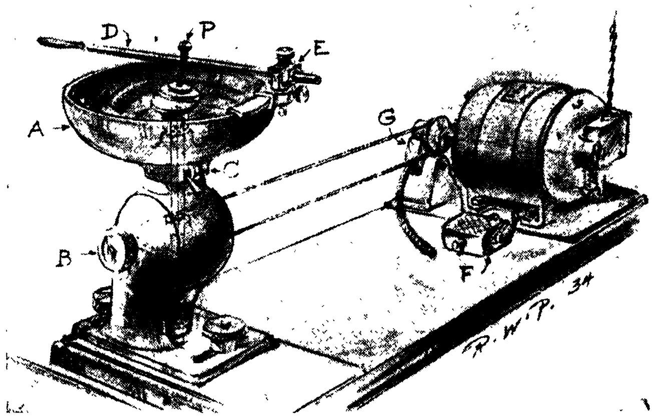


Figure 1

up a few more ideas on the subject since writing the chapter on eyepieces (page 66, "Amateur Telescope Making,") and am here offering them to the "fraternity," along with a description of the spindle I have been using here at Pasadena the past few years.

Figure 1 shows the general set-up, the spindle and motor bolted to a cast iron slab. The motor is 1 h.p. (1725 r.p.m.) giving ample power for the larger work running up to 2½″ diameter. The spindle is 6″ long, 7/16″ in diameter and runs in ball bearings. The dish *A* is removable, and a horizontal stud at *B* allows turning the spindle easily into a horizontal position for centering work. The dish can be clamped, *C*, in any azimuth so as to bring the lever arm *D* to the most comfortable position. The lever arm is provided with a universal joint *E*, and the rod itself can be slid endwise and rocked, so as to bring the pin *P*, carrying the lens, to just the right place over the lap. Two pulleys on the motor and two on the spindle, of 5/8″, 1″, 1½″, and 2″ diameter, allow a wide range of speeds for the different sized lenses.

I experienced trouble with the belt, trying different materials in order to obtain the smoothest action and longest life. The one on the machine now is the most satisfactory. It is leather, round, and has no joint, and was cut from a strip of 4″ belting (*a*, Figure 6). Slots in the base permit taking up the stretch. My last addition to the machine is locating the starting and stopping switch *F* within easy reach—for the left hand is usually occupied holding the lever that controls the spinning lens—also the provision of a brake *G* for quickly bringing the motor armature to rest.

The amateur, in attempting his own machine, may well disregard certain features shown in my design, for this instrument was made with the resources

FIGURE 2

of a large machine shop. The patterns were all expensively cored, the castings aluminum. But the essential features should be retained—namely, a smooth running spindle (plain bearings will do, but must be kept carefully oiled and protected from grit), a smooth running belt, a detachable dish, and provision for bringing the spindle to a horizontal position.

With the machine so described it is unnecessary to depend on a lathe for turning up the various curved surfaces on the brass laps, for you are virtually already provided with a speed lathe set up on end. A very little practice with a hand tool made out of an old file, using the lever arm as a steady rest as shown in Figure 2, will form a lap in a few moments so that it fits its templates.

Of course, for good work, the laps should be made in pairs—male and female—and ground together. Much time will be saved in holding the laps to their correct curvature, if the bulk of the glass has first been removed from the glass blank, before placing it on the machine. (See "A.T.M.," p. 67, Figure 53, *b*.)

I am now using four grades of abrasives: Nos. 90, 1F, and 600 Carborundum, and 305 emery. The addition of an equal amount of talc to the emery will almost surely prevent scratches in the final grinding. It leaves the glass

with a surface that comes to a polish in a few moments. Scratches usually show up with 600 Carbo. A fruitful cause is letting the lap become too dry. It doesn't take long for the rapidly rotating tool and spinning lens to move the lubricant away from their central areas. Should the worst happen the lens will seize to the pitch, the pin on the lever arm will jump out of its pivot, and the lens may fly off into the dish and very likely suffer a chipped edge. Perhaps a hardwood dish, or a dish of some material that will cushion such a blow, would be advisable.

I find it pays to do some thorough house cleaning when changing from one grade to one finer, also that it pays to put down fresh newspapers, to

FIGURE 3

scrub the hands well with a scrubbing brush and clean the finger nails. My four grades of abrasives are kept in four glass cups—caster cups—(at the five-and-ten, at a nickel each). I ground their edges on a sheet of window glass, then cut up the window glass into cover plates for them.

In polishing I cover the tool, or lap, with only about $\frac{1}{16}''$ of rather hard pitch and, while still warm and rotating on the spindle, smooth it up to shape with its mate (wetted). The prepared fine-ground lens will do about as well. The rouge polishes faster if the pitch is rechanneled often. It only takes a moment with the blade of a pen knife, and Figure 3 shows the way I do it. The pitch at the center of the tool can well be removed, for it permits the pitch under pressure to flow toward the center as well as the edge.

The tyro must work out his own salvation until he knows just how far to let his spinning lens move away from the center of the rapidly revolving tool, in order to have the polish come up evenly on the glass. He will notice that, with the center of the lens directly over the center of the tool, they

are both going at the same r.p.m.—they are as one—and no action is taking place. Theoretically, and assuming perfect contact and also assuming that the tool retains its shape (which it never does), a position for the lens center from the tool center will be found when the lens ceases to spin and comes to rest, and beyond that critical point it will start spinning in the other direction. But pitch, as mirror makers know to their sorrow, is queer stuff, and possessed of seven devils, and one must find for himself about how far the lens should pass across the tool.

What is actually taking place between the glass and pitch surfaces is rather complicated. In Figure 6, *b*, with the tool rotating anti-clockwise as shown, the areas on the tool at *A* and *C* will tend to give the lens the same rotation as the tool. But around *B* the tendency of the tool is to turn the

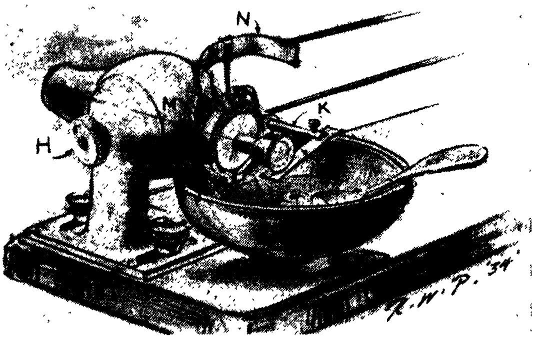


FIGURE 4

lens in the opposite manner, namely, clockwise. Moreover, heat is being generated, the pitch is flowing, and the slope of the surfaces is continually changing with the stroke.

In general it can be said that enlarging the central cavity in the tool will bring more of the polishing action to the outer parts of the lens, and trimming down the size of the tool to less than that of the lens will have the opposite effect. The length of stroke is, of course, important.

As with mirrors, it is desirable to remove the lens as few times as possible. I use a match-stick to apply a drop or two to the lap when necessary. By carefully moving the spinning lens so as to expose as much of the center of the tool as is safe, the rouge is applied at the center and allowed to work outward by centrifugal force.

The danger of producing zones by paring away the tool at center or edge might argue for a full-sized tool, uniform throughout, the exact counterpart (obverse) of the lens surface itself. Zonal irregularities become apparent when two lenses with contact surfaces—say flint and crown of an achromatic

doublet—are viewed under monochromatic light. The interference rings are not evenly spaced, there are too many of them, and they depart from circles as the lenses are moved eccentric to each other.

Centering comes next. When the lenses are polished, the dish is removed, the clamping nut *H* (Figure 4) unscrewed and the spindle brought horizontal. For centering I use an attachment (Figure 4) that slips over the seat formerly occupied by the dish. This gadget comprises the rod *K* carrying the edging plate *L* and a screw *M* acting against an arm of *K*, and the guard *N*. The right adapter (*A*, in *c*, Figure 6) is pressed on the tapered spindle end and a little hot pitch daubed on the flange at *B*. With the flame of a bunsen burner (Figure 5)—an alcohol lamp will do as well—the adapter and spindle end are given a warming and the lens cemented against the flange *B* (Figure

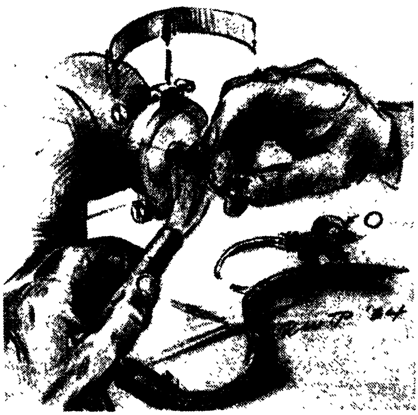


FIGURE 5

6, *c*). By giving the spindle a few turns and looking at the lens, the reflections from the lens (of different parts in the room, lights, and so on) will be seen to wobble. The lens is then moved a trifle on its seat and the spindle again given a turn. If you have reduced the wobble—if the reflections show less movement—you moved the lens in the right direction. If not, and it has increased, you have made a bad matter worse. A few tries and the secret is out and you know which way to move the lens to reduce the wobble and finally to wipe it out altogether. What you see in the lens as it rotates remains fixed. The axes of the spindle and the lens coincide. Probably the pitch has cooled off before the job is done, but a few passes of the flame allow the adjustment to be carried on indefinitely.

We are now ready to edge the lens. On goes the edging plate *L* (Figure 4), and the screw *M* is advanced until the edging plate just touches the lens. The dish is placed as shown, with some 1F Carbo and water in it, and a

spoon. The motor is started, the guard *N* dropped and the Carbo spooned on to the edging plate. As the plate is brought to bear on the lens under the action of screw *M,* and the Carbo is dragged under the lens edge, the ear detects a vibration of the plate due to the pounding cam action of the lens. In a short time, as the glass wears down, this pounding disappears and one has only to watch with an outside calipers (*O,* Figure 5) for the

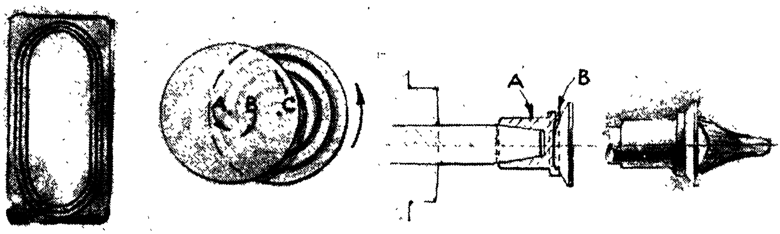


FIGURE 6

a *b* *c* *d*

lens to come down to the required diameter. The lens is removed under a little heat, placed in kerosene (or gasolene) over night, when it can be washed clean with soap and water.

What I have here described (as well as in Chapter XI, page 66, "A.T.M.") are the wrinkles and methods worked out by myself without being prejudiced by a knowledge of professional practice. Undoubtedly some of them will appear crude and amusing to the professional. For example, it may be that a better way of making a lens run true on a spindle is to use a fork (*d,* Figure 6) and, as explained on pages 69–70, "A.T.M.," I have used them both, but I remember a bad scratch that developed when I used the fork. There may be other simpler and more orthodox ways, but it's been lots of fun working out one's own technic.

To me a lens is a wonderful and beautiful object, and I shall be well repaid if what I have described starts others of our now large following of telescope makers to try equipping their instruments with their own oculars.

An Introduction to Small Lenses

By R. E. Clark
Langeloth, Pennsylvania

The practical instructions on small lens making given in the popular books on telescope making do not go into enough detail to enable a beginner to make a really satisfactory lens.

Nearly all amateurs require minutely detailed instructions to start with, but with practice they become more expert, and find their own way around the pitfalls which are sure to develop.

The making of optical goods is one of the most highly specialized crafts there is, and yet your ordinary amateur usually expects to go ahead and do first-class work, practically without instructions.

The following notes and sketches are the result of several years of practical lens making experience and, what is more important, contain the answers to numberless questions put to me by other amateurs.

I would suggest that copies of Orford's "Lens Work for Amateurs" and Lockett's "Camera Lenses" be secured and thoroughly mastered before taking up the actual work. Orford's methods are rather tedious and slow, but with patience they will give beautiful results. His cloth polishers do fine work in expert hands, but unless one has some little dexterity at the work they are better left severely alone.

The notes which follow were written with the thought that explicit detail, even at the risk of becoming rather boresome by continued repetition, would tend to make a rather exacting job a little simpler. Parts of these notes have been taken directly from other authors—not with the thought of passing them along as my own creation, but simply because such parts were of prime importance and very aptly put. Bear in mind at all times that accuracy is paramount, and unless you have a natural aptitude for detail, don't expect to rival Ritchey, Brashear, Porter & Company—it can't be done.

Cold rolled steel and brass bars:
  Williams & Company, Pittsburgh, Pa.
  C. H. Besley & Co., Chicago, Illinois.
Cast iron for laps:
  J. H. Morrison & Co., Oliver Bldg., Pittsburgh, Pa.
Glass:
  Pittsburgh Plate Glass Co., Pittsburgh, Pa.
  L. D. Keller, 2344 Nineteenth St., Philadelphia, Pa.
Lathes:
  South Bend Lathe Co., South Bend, Indiana.
  Atlas Press Company, Kalamazoo, Michigan.
Grinders, pulleys, shafting, etc.:
  Sears Roebuck & Co.,
  Montgomery Ward & Co.

Chaser's cement, optician's tools, etc.:
Wm. Dixon & Sons, 34 Kinney St., Newark, New Jersey.
Surfacing machine:
Shuron Optical Co., Geneva, New York.

Tools and Curves

It is the usual procedure in starting an article of this nature to give a list of tools and materials. The following list takes care of the absolute necessities, and your ingenuity will probably suggest a number of variations, any or all of which may or may not be in order. Try them, anyway; it may add a small measure of zest to your other tribulations.

First and foremost is a small engine lathe, which should be capable of handling work 8" in diameter. Length of bed is of little consequence, as

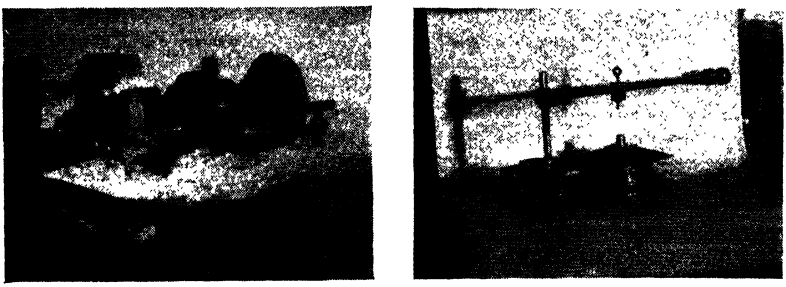


FIGURE 1
Left: Grinding stand. Right: Vertical spindle.

most of your work is under 18" long. It should be equipped with a four-jaw independent chuck, be capable of cutting up to 40 threads per inch, and be adjustable for turning a taper. Several such lathes are on the market, costing at present (1935), complete with motor, about $100.00. Get as good a machine as you can possibly afford.

Practically all the operations of lens making can be done on a lathe, but it is not wise or advisable to use such a machine for glass working, as a good engine lathe is easily ruined by Carborundum and water and, conversely, a good lens will be utterly ruined if it is dropped on the iron bed of the lathe. A lathe is, however, an absolute necessity for turning and truing laps and gages, and in making mountings for your finished lenses.

Accessories for the lathe should include a cut-off tool, a medium knurl, and a Jacobs or other first-class chuck capable of taking a ½" drill.

Purchase a small double-ended grinding stand (mail order house—Montgomery Ward & Co., Sears Roebuck & Co., etc., see Figure 1, left), equip on one side with a 1" face, 80 grit, Grade G5, 6" diameter Carborundum wheel, and arrange a splash pan and guard for wet grinding. The other end of

the spindle should have a vitrified bond Carborundum wheel—about 60 grit, ½″ face. This last is used for tool sharpening and miscellaneous grinding; it is used without water. When buying your stand, purchase a wheel dresser —true wheels are essential. This point cannot be emphasized too strongly, as a wobbly wheel is an abomination, and will simply result in broken glass and sore fingers. Do not over-speed your wheels, also keep your head to one side while grinding, since serious injury can result if a wheel breaks.

The third essential tool is a vertical spindle (Figure 1, right), arranged to run at four speeds: 100, 300, 500 and 700 r.p.m., and having at its upper end a taper and an internal, female thread, into or over which your various laps will fit.

If you live near a larger city, arrange to visit a manufacturing optical shop or a spectacle grinder's. Ask to see a "surfacing machine." Ten

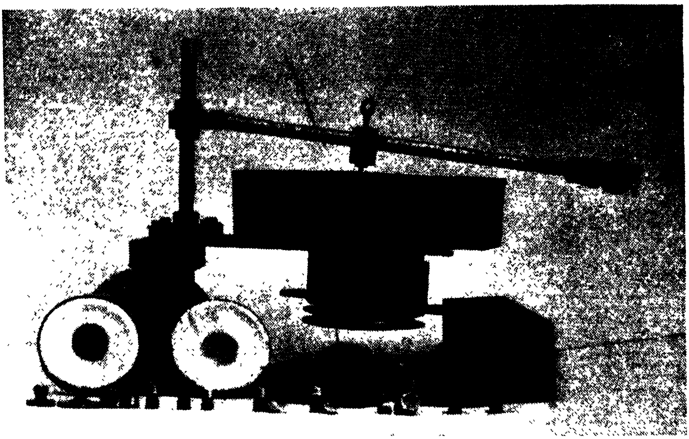
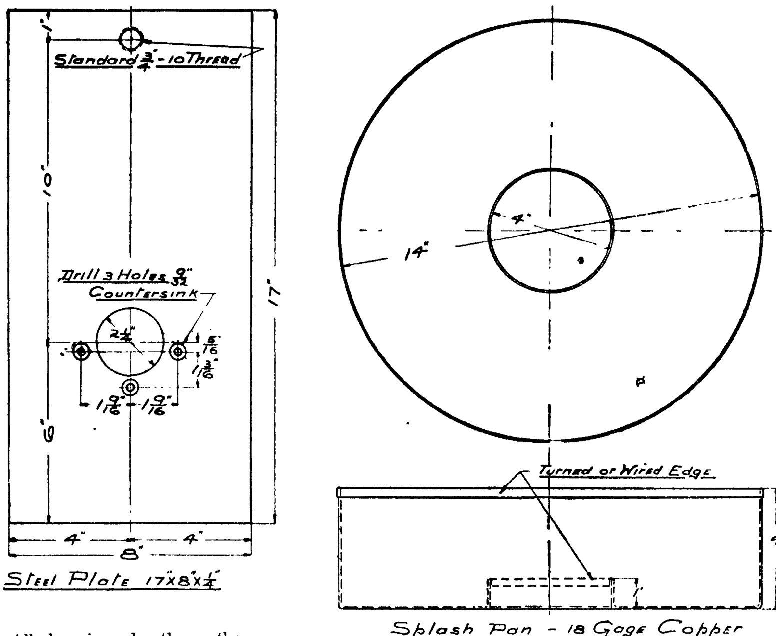


FIGURE 2

Close-up of spindle shown in Figure 1. Some of the small work to be described later in the chapter shows below it.

minutes' close observation will give you more dope than a whole chapter of instructions. Notice particularly the arrangement for stopping and starting, by means of a knee or foot switch (I use an auto dimmer switch which, although built for 6 volts, has lasted three years with 110 volts). Also notice the means by which the pin bar is swivelled, also the adjustment of the pin on the bar. A few judicious questions will elicit a world of information. If you are one of those fortunate people who have lots of money, by all means buy a factory-made surfacing machine. However, we shall take it for granted that you will make your own spindle. The photographs and drawings should make clear the general arrangement.

To make one, procure an old Ford generator, Model A-1929, and strip all the coils from the case, also remove everything from the shaft except the bearing cones. Be careful not to bend the shaft. Save all the screws and bolts—they will be used in reassembling. Clean thoroughly and reassemble. Both ends of these shafts have a taper. Buy a die-cast, 6" diameter, "V"



All drawings by the author

FIGURE 3

Details of the vertical spindle.

belt wheel (mail order house—about 75¢) and taper the bore accurately to fit the end of the shaft which projects from the open end of the generator case. Fasten with the original cap screw and washer. Also drill and tap the hub of the wheel for a 1/4" set screw, making a good tight job. Place between the centers in your lathe and true up the groove and rim of the wheel with the axis of the shaft bearings. The other end of the shaft will carry your laps and should be equipped with a tapered nosepiece and splash guard (Figures 2, 3, 4). This splash guard acts as a deflector and keeps grit and dirt away from the spindle bearings. It is made slightly larger in diameter than the central hole in your grinding pan.

Procure three pieces of 2" x 2" x 1/4" angle iron 1" long and fasten them

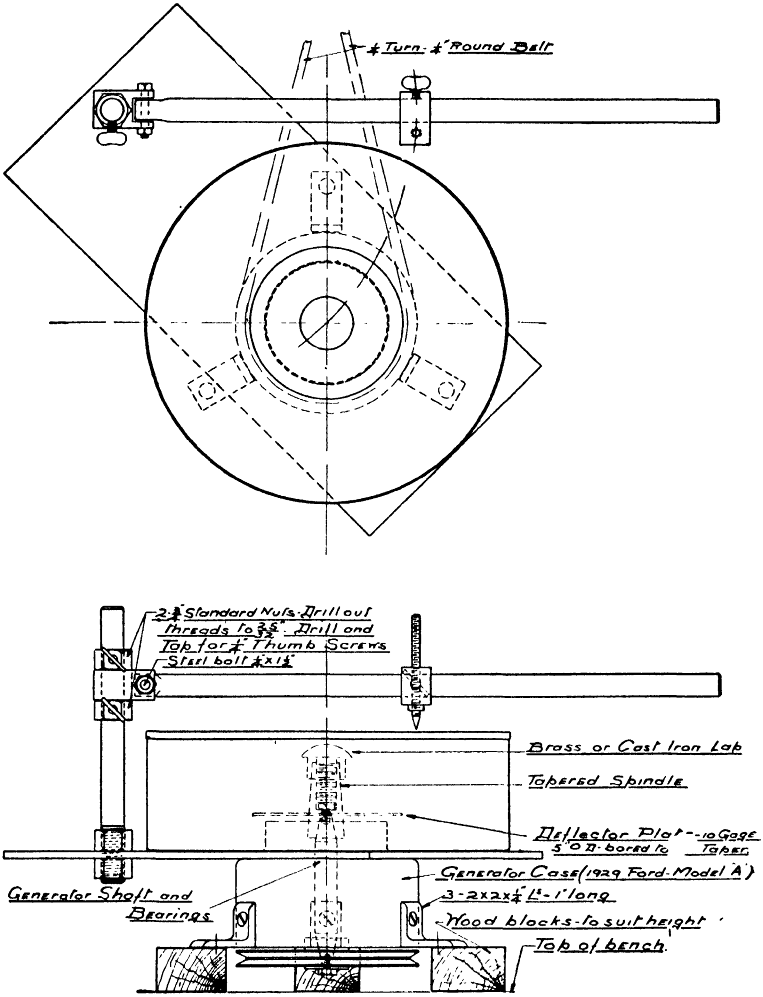


FIGURE 4

Details of the vertical spindle.

(with the coil screws) to the outside of the generator case—these form feet (Figure 4), which in turn will be bolted to blocks mounted on your work bench.

A piece of ¼″ boiler plate 8″ wide and 17″ long is next fitted on the upper side of the generator case and firmly bolted to it. This plate forms the table for your splash pan, and also has screwed into it the pin bar shaft.

The assembly and details of these pieces is shown in Figures 3, 4, 5 and photo of the author's spindle (Figure 2) which shows the splash pan in position.

The foregoing three machines—lathe, grinding stand and vertical spindle—are indispensable. A small drill press will prove very useful, but is not absolutely necessary.

If, as I imagine, you are already a hobbyist, you doubtless have some of the following hand tools and materials:

2″ micrometer with an adapter to take from 0″ to 1″.

A 6″ steel scale or combination square with scale and centering head. (Fig. 21380, Wm. D. & Co.—$2.40).

One double-ended brass calipers for gaging lenses. (Fig. 21315 Wm. D. & Co.—25 cents *).

One each, inside and outside, 4″ screw-adjusting calipers. (Fig. 21358–9, Wm. D. & Co.—$1.10 ea.).

One small center drill.

One thread gage.

Some 6″ and 8″ smooth files, also several old files 6″ to 10″ long (to make into scrapers and hand tools).

1 lb. pine or coal tar pitch.

½ lb. Chaser's cement—black. (Fig. 20347–2—35¢, Wm. D. & Co.).

1 jeweller's loupe, 1½″ focus (a good magnifying glass will serve). (Wm. D. & Co., Fig. 21512 No. 8—75 cents).

1 alcohol lamp or bunsen burner.

1 lb. each, No. 80–220–F–600 Carborundum grains (buy original packages) (Carborundum Company, Niagara Falls, N. Y.—50 cents lb.).

1 lb. No. 6F emery (Hamilton Emery Co., 30 Church St., New York).

1 lb. rouge, M309 (American Optical Co., Southbridge, Mass.).

Several pieces thin brass sheet, 16 or 18 gage (scraps 3″ wide or over are large enough) (Williams & Co., Pittsburgh, Pa.).

Brass tubing—all $1/32$″ wall, in 12″ lengths and the following diameters: ¼″, ⅜″, ½″, ¾″.

Brass tubing (for eyepiece mounts), $1/16$″ wall, 1¼″ O.D.—24″ lengths.

Brass tubing for adapter tubes, $1/32$″ wall 1¼″ I.D.—12″ lengths. This last item should telescope easily over the 1¼″ eyepiece tubing. All of the

* The author states prices as of 1935, but many of these will vary from time to time. Therefore prospective purchasers perhaps had best obtain current prices before remitting. The amounts stated above will nevertheless, serve to give a general idea of costs.—*Ed.*

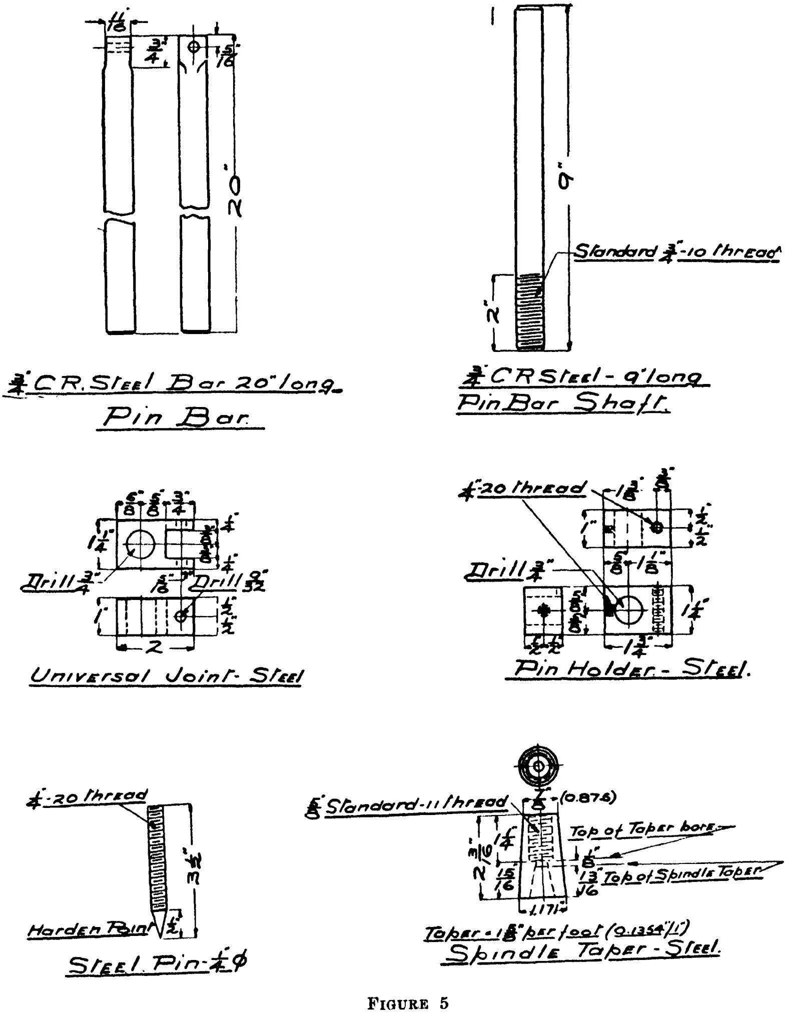


FIGURE 5

Details of the vertical spindle.

above sizes of tubing may be procured from Besley & Company, 118 N. Clinton St., Chicago, Illinois.

6″ each rolled brass bar 1¼″, 1½″ and 2″ diameter.

Some odd pieces of cold rolled steel from 1″ to 2″ in diameter.

The Relationship between the Focus and Curve

I will endeavor to explain briefly the relationship that exists between the curve of a lens and the focus of a lens. This work is not intended for the advanced worker, but only for the beginner. Higher mathematics are

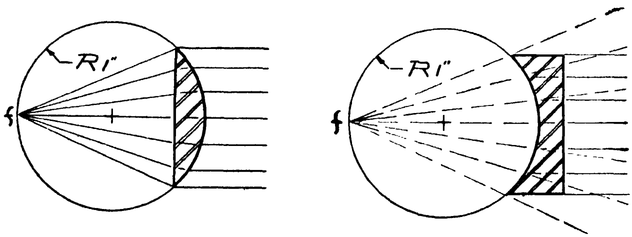


Figure 6

Left: Plano-convex lens ($f=2R$). Right: Plano-concave lens ($f=2R$).

not only unnecessary here, but will prove bewildering and can serve no useful purpose. If, however, you are of a mathematical turn of mind, see the articles in the latest "Encyclopedia Britannica" under ("Lenses," 13th ed., 6 pp., and under "Microscope," 13th ed., 10 pp.) or in Conrady's Works, etc.

Focus

The focus of a lens is that point to which the lens will converge parallel rays of light. Figure 6, at left, is a sketch of a plano-convex lens. Its F

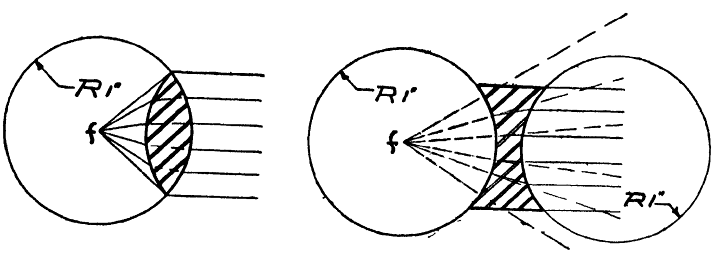


Figure 7

Left: Bi-convex lens ($f=R$). Right: Bi-concave lens ($f=R$).

(or focal length) is for all practical purposes equal to the diameter of the sphere or circle of which its curved surface forms a part. Thus, in the

illustration, if the circle is of 1″ radius, the F of the plano-convex lens would be 2″. In other words, F = 2R.

Exactly the same relationship exists in the plano-convex lens illustrated in Figure 6, right, except that this has only a virtual (imaginary) focus and

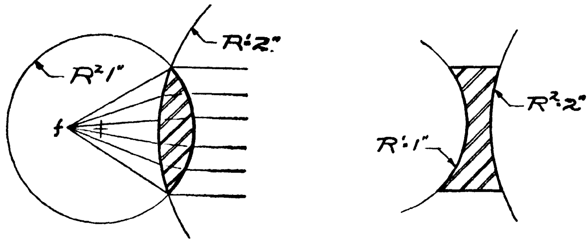


FIGURE 8

Left: Crossed convex lens (f=1.33″). Right: Crossed concave lens.

cannot by itself cause the convergence of rays to a point; it actually causes a divergence.

A bi-convex lens, Figure 7, left, having both curves of the same radius, has a focus equal to that radius (F = R). A bi-convex lens which has the same radius of curvature as a plano-convex has, therefore, only of one half its focal length. This also holds true in the case of a bi-concave or double-concave lens (Figure 7, right).

The refractive index of the glass used has not been considered in the above figures. The result, however, is very nearly exactly as stated, with ordinary crown or plate glass.

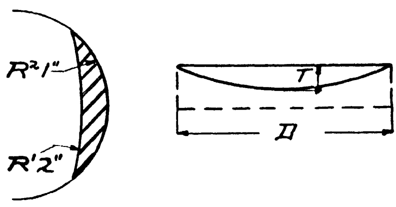


FIGURE 9

Left: Positive meniscus lens. Right: Plano-convex and plano-concave.

To avoid the confusion which exists in many texts on optics, the following convention has been adopted throughout these notes: All convex surfaces are plus and all concave surfaces are minus—this, regardless of the direction of impinging light rays.

The focus of either a crossed convex or concave lens (Figure 8, left, and Figure 8, right) having curves of different radii, may be simply calculated as follows:

R_1 equals the radius of one curve and R_2 equals the radius of the second curve:

$$\frac{R_1 \times R_2 \times 2}{R_1 + R_2} = \text{focus of lens.}$$

As an example, the first radius, R_1, is 2″, the second radius, R_2, is 1″. Then:

$$\frac{2 \times 1 \times 2}{2 + 1} = 4/3 \text{ or } 1.333'', \text{ the focal length of the whole lens.}$$

Lenses may have one convex side and one concave side. If the convexity predominates, so that an image of a light is formed, then the lens is called a positive meniscus (Figure 9, at left).

If the concavity predominates, it is called a negative meniscus.

The above formula is used to calculate these meniscus lenses, except that a plus sign should precede a convex radius and a minus sign the concave radius. For those who are rusty in their mathematics, remember that, when multiplying or dividing quantities with like signs, the product is plus. If the signs preceding the quantities differ, then the product will be minus. When adding unlike signs, subtract one from the other and affix the sign of the greater to the answer. If both have like signs, the answer will have that sign. In subtraction, change the sign of the quantity subtracted, and add the quantities together. As an example, a meniscus lens has a plus (convex) radius of 2″, and a minus (concave) radius of 3″. Then:

$$\frac{(+2) \times (-3) \times (+2)}{(+2) + (-3)} = \frac{-12}{-1} = 12'' \text{ focus.}$$

It is often necessary to duplicate a broken lens. This may be managed in the following way: The thickness of the convex lens, or the depth of the concave lens, may be measured with a micrometer or double calipers. Figure 9, right, represents in full line a plano-convex lens, while a plano-concave lens is shown in dotted line. *D* is the diameter, and *T* the thickness. The radius of the curve will be—one fourth the square of the diameter added to the square of the thickness or depth, and this sum divided by twice the thickness:

$$\frac{\frac{D^2}{4} + T^2}{2\,T}$$

As an example: A plano-convex lens has a diameter of 1″ and a thickness of ¼″ at the center.

$$\frac{\frac{1x1}{4} + (.25 \ x \ .25)}{2 \times .25} = \frac{.25 + .0625}{.5} = \frac{.3125}{.5} = .625''.$$

As it is a plano-convex lens, the focus is twice the radius, or 1.25″.

Opticians use a spherometer, a small instrument with three fixed legs and one movable graduated leg, for finding the curve of lenses.

It is possible to continue giving formulae and definitions but, as mentioned

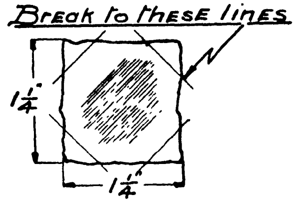


FIGURE 10
Glass blank

above, these are not necessary to the beginner and only serve either to bewilder him thoroughly or else discourage him completely.

MAKING A LENS—BLANKS—ROUGHING

We will start with a definite purpose in view—and will take as our example a plano-convex lens of 1" radius. It will have a focal length when finished of 2" and it will be very useful as a magnifier in your other work. A thickness in the center of 3/16" will give a diameter of approximately 1⅛".

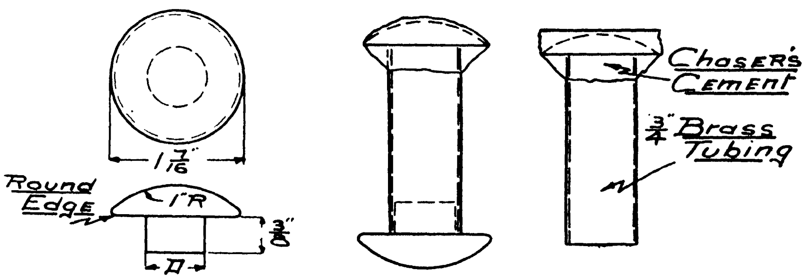


FIGURE 11

Left: Brass handle. D 1/32" less than I.D. of tubing. Center: Roughed blank mounted ready for grinding. Right: Mounted blank.

Procure a piece of "Crystallex" plate glass (The Pittsburgh Plate Glass Company) several inches square and ¼" thick. If this glass is not available, use ordinary windshield glass. Cut out, with a glass cutter, four pieces, each 1¼" square. Break off the corners of these squares with your pliers, so that your blanks are roughly circular. Lightly grind one polished side of each on your wet Carborundum wheel (Figure 10).

Cut four pieces of ¾″ brass tubing 2″ long. Do this in your lathe, so that the ends will be square and smooth.

Turn up a small brass handle with a shank ⅜″ long and 21⁄32″ in diameter (Figure 11, left and center). This will give an easy fit inside of ¾″ tubing. A radius of about 1″ will fit your palm, and will prevent blisters.

Place your blanks over your burner, interposing a 1⁄16″ sheet of asbestos between them and the direct flame. Allow them to heat up until, on touching a piece of Chaser's cement to the upper slightly ground surface, it will melt and form an even coat all over. Remove from the heat and place on your work bench.

A word here regarding your bench surface: Keep it clean, and covered at all times with paper—magazine paper which has a shiny finish is preferable to newspaper.

Take one of your brass tubes and heat it. Apply Chaser's cement to one end, rotate in the flame and get a liberal quantity to stick, place directly on your still warm blank, center as closely as you can, and allow to cool somewhat. With the mounted lens in one hand, apply by melting and dropping, some more Chaser's cement to the back of your blank. Carefully pass it through the naked flame and, with the moistened fingers, form a neat smooth surfaced joint, Figure 11, right. Make sure of a good job, as nothing is more annoying than to have a lens fly from its holder. Set up all four of your blanks. On your wet Carborundum stone grind each of your blanks as nearly circular as you can. Also shape the surface to your template as closely as possible. Allow perhaps 1⁄16″ over your finished diameter for finishing. When roughing out your curve, it is well to leave a spot of polish 1⁄16″ or so in diameter in the center of the blank. This will enable you to keep your rough curve fairly central.

Gages and Laps

Cut two squares of 16- or 18-gage sheet brass—one 3″ x 3″, the other 2¼″ x 2¼″. Clean both with emery paper. On one side of each, scratch diagonal lines and lightly prickpunch the center. Next drill two ⅛″ holes. These holes are for stringing your gages together—otherwise they will surely get lost. If you have a small set of figure punches, mark the radius on each piece plainly. Do not wait until your gage is complete before punching your marks—to do so will inevitably lead to distortion of your curves, which must be avoided at all costs.

Convex (*Male*) *Gages:* In the center of one side of your 2¼″ square, securely sweat a short piece of ½″ round brass rod (any small scrap that you can hold in your lathe chuck will do) and chuck it in your lathe, true up by the corners and turn to exactly 2″ diameter (use your mike). Bevel both sides of the edge ¼″, leaving the edge 1⁄64″ wide. Do not attempt to finish either the bevels or the edge with emery paper—use a sharp tool and get as true a circle as possible.

Concave (*Female*) *Gages:* Next, chuck your 3″ square. Use just enough pressure to hold the piece firmly. Center by your prick punch mark. Drill

and bore a 2″ hole, bevel the sides 1/4″ back, leaving the edge 1/64″ wide. At the risk of being tiresome I repeat: Do not use emery paper on the edge of the gage—use a sharp tool. Use your convex gage to get an accurate fit.

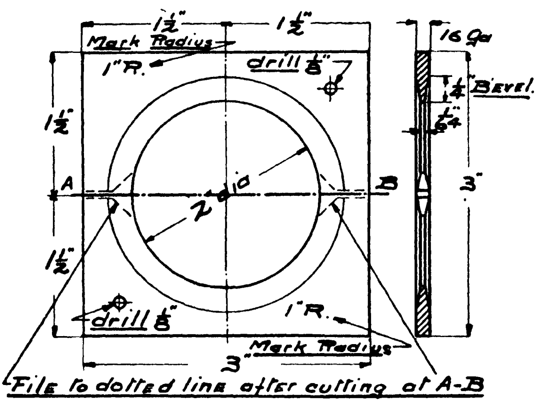


Figure 12
Concave templet, 16-gage.

A good push fit is what you are after. Take plenty of time and work accurately—1/1000″ is too much between gages of this size.

Next, use a hack saw (do not use shears or hammer and chisel) and cut in two on the line *AB*, Figure 12. This will give you two concave gages. Bevel each corner 1/4″ with a file. Check both gages against your convex

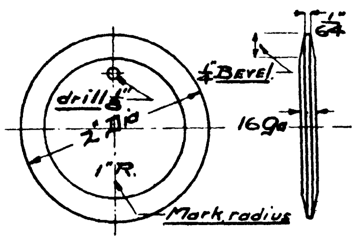


Figure 13
Convex template, 16-gage.

gage. If your work has been accurate you should not be able to see light between your gages when they are held between the eye and a strong light. Figure 13 shows your finished gages. Small gages may also be bored and turned from solid bar stock.

Lap Mandrel: Before making a lap, it will be well to make up a fixture or jig. This will insure true running laps and is also a great time saver. Procure a piece of cold rolled steel 6″ long and 1⅛″ in diameter. On one end turn a standard taper to fit your lathe spindle. Place the tapered end

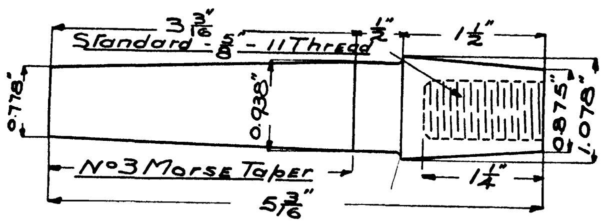


FIGURE 14
Taper mandrel.

in your lathe spindle, face and turn the projecting end to a taper of 1⅝″ per foot (0.1354″ per inch) for a distance of 1½″; the end diameter being ⅞″ (0.875″) and the larger diameter 1.078″ (0.875 + 0.203). Between the two tapers turn to 0.938″. Bore and thread for a ⅝″ standard 11 thread to a depth of 1¼″. It is well to mark your lathe compound rest with the exact

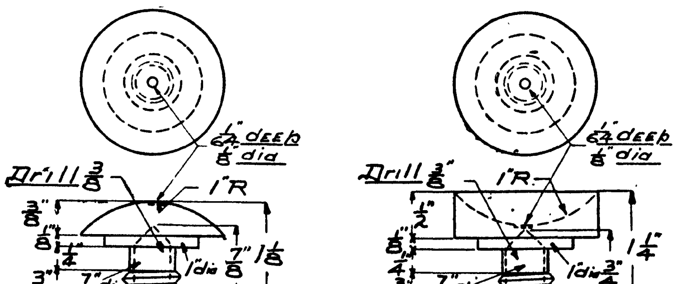


FIGURE 15
Left: Convex lap. Right: Concave lap.

degree of your 1⅝″ per foot taper. Your larger laps will be fitted over this taper, and marking your slide rest now will save lots of time and trouble later. Figure 14 shows this taper mandrel.

Laps: Chuck a piece of 1½″ diameter brass or fine grained soft cast iron bar, using your tail stock center to steady the work. Turn to ⅝″ diameter for a distance of ⅝″ (Figure 15). Relieve to 7/16″ diameter and thread the ⅝″ portion. Make an easy running thread. It is well to get a standard ⅝″ bolt and nut and to use these as standards for all of your threads. Turn

down the next ⅛″ to 1″ diameter, being sure that your 1″ diameter face is true. Drill or bore a ⅜″ hole ¾″ or ⅞″ deep. Finish the bottom of the hole conical. Cut off to 1¼″ long over all. Make several of these lap blanks.

Convex Lap: Place your taper mandrel (Figure 14) in your spindle and tap it home with a piece of wood. Screw a lap blank into the projecting end. The reason for square faces on your jig and laps is now apparent—if

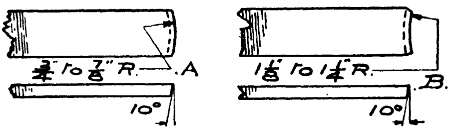


FIGURE 16
Hand tools.

they were not square, your lap would wobble. Turn up your curve as nearly as possible and finish with a hand tool. Figure 15, at left, shows a completed convex lap and the same figure, at right, shows a concave.

Good hand tools for finishing laps can be made from old flat files. Grind smooth on all four sides for about 2″, round the end, as shown in Figure 16, giving the end a rake of about 10°. Heat red hot and plunge in either water or kerosene oil. The tool shown at the left is for concave laps and the one at the right for convex.

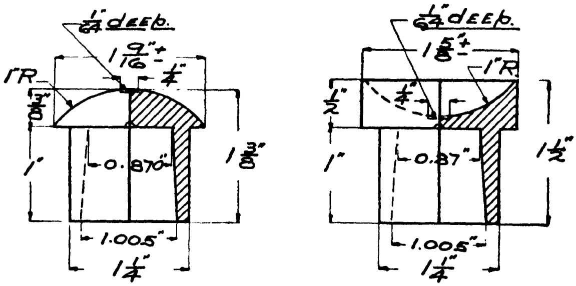


FIGURE 17
Left: Convex lap. Right: Concave lap.

Run your lathe fast when using these tools, and take extremely light cuts—almost scrapes. With a little practice a pair of laps can be accurately fitted to their templates and to each other in a very short time.

A small spot $\frac{1}{16}$″ to ⅛″ in diameter and perhaps $\frac{1}{64}$″ deep should be taken out of the center of all your laps. Very little grinding is done on this part of the lap. This slight depression should be kept open at all times. It serves as a reservoir and aids in giving a better distribution of Carbo and emery.

The foregoing instructions are for making a lap which screws into your

spindle. In making very small laps it is of advantage to be able to use 7/8″ or 1″ round brass stock, thus making quite a saving in material and time over the generally used female taper lap, the shank of which has in all cases to be at least 1¼″ in diameter. For laps 1¼″ or larger in outside diameter, the taper method of driving is far preferable.

Procure a piece of 1½″ or 1¾″ round brass or cast iron stock, chuck and center carefully, turn to 1¼″ diameter for a distance of 1″, bore to the same depth, and very carefully taper this bore 1⅝″ per foot (see Figure 17, lower part of either drawing). A small conical hole 1/16″ deep should be turned in the center of the bottom of the bore (this will enable you to spin one lap on another when grinding curves together). The diameter of your bore should be such that there will be a space of ⅛″ to 3/16″ between the top of your mandrel and the bottom of the bore when the former is tapped into place.

Dimensions of this taper bore are given in the same drawings. Cut off your blank to the desired length and finish the convex or concave surface with the lap mounted on your mandrel (Figure 14).

It will probably save some little time, however, if you put the final finish on your laps by grinding them together. Great care, however, should be exercised in doing this, as it is very easy to get away from your template curve. After hand turning the laps as closely to the template as you are able, screw the convex lap in your spindle, moisten with water, and apply a little moist 220 Carborundum. Place the convex lap on top, adjust your pin bar horizontal, and your pin square to the curve of the convex lap. Insert the pin in the ⅜″ conical-bottomed hole in the back of the concave lap and, with a back and forth movement, allow the concave lap to spin freely. Use your lowest speed. After half a minute stop your machine and wash up the convex lap. Match it to your template. Experience will teach you how long your laps should be run together.

Should your concave lap become too deep in the center, screw it into the spindle and allow the convex to spin on top, or with the convex lap in the spindle, and the concave held almost, but not quite, central over it. Run together for a short time, when the edges of the concave will become slightly flattened and so brought back to the template curve. Variations of position of the laps with regard to each other, will be found to have very different grinding actions and, as in mirror making, length of stroke, etc., will have very definite uses in altering your curve.

It will be found in general, that in the earlier stages of grinding, a true lap cannot be made to generate a true curve on the glass. This may sound paradoxical, but it is nevertheless a fact. In making a convex lens (either mounted on a hand holder or by the spinning method) the glass tends to be too high in the center. In other words, your curve becomes of a smaller radius than its template. In order to offset this tendency, I always fit my concave laps so that they touch the template in the center and have a few thousandths of an inch clearance at the periphery. With a concave lens the opposite tendency will be noted (that is, the lens curve tends to deepen too

much in the center) and the template, therefore, should be made to fit the edges of the lap and be slightly clear toward the center. However, if you are a beginner, it is advisable to get your laps as close to your templates and to each other as you possibly can.

Roughing Out: Screw your concave lap in the spindle, and at 100 to 200 r.p.m. proceed with No. 80 Carborundum to roughing your blanks to curve. Keep moving your blank across the lap in arcs, at the same time allowing it to rotate every once in a while on the brass handle, which should be held in the palm of your hand. A little dexterity is required to do this properly. From time to time apply a little Carborundum and water to the glass. Keep it in firm contact and examine frequently with your lens. Stop when no more marks of your preliminary grinding on the Carborundum stone can be seen. Do not pay too much attention to the curve at this stage. Rough out all four blanks. Wash up everything and place clean papers on your bench.

A word here about your Carborundum. For each grade that you have, including emery, procure a glass caster cup about 2½" or 3" in diameter (5 and 10 cent store). Cut squares of window or plate glass ½" larger than the O.D. of the cups, and smooth up the edges of these pieces on your wet Carborundum stone. With a little 220 Carborundum and water, grind the edges of each cup on one of the squares of glass. Wash up thoroughly and keep each square glass cover on its own individual Carborundum cup at all times. I have used these caster cups for several years, and after trying tin boxes, salt shakers, sprinkler bottles, etc., I fully agree with Mr. Porter that they are by far the best scheme so far devised to keep your Carborundum uncontaminated. Mix a little water with each grade and use your fingers or a match stem to apply the Carborundum to the glass when grinding. A few drops of alcohol in the finely ground grades makes them easier to wet down, and 5 or 10 percent of fine talcum in your 6F emery may save scratches. Be careful not to get a coarser grade into the finer grade. Wash your hands frequently, keep your finger nails clean. Use plenty of changes of paper on your bench and bear in mind that, "cleanliness is away ahead of godliness" as a preventive of scratches.

Your blanks are probably quite a bit off curve, especially the last one run. Take it, No. 4, and grind for 30 seconds with 220 Carborundum. Wash, and try it with your template—if it is nearer to the curve than it was before this treatment, give it a second short shot and repeat until no more improvement in the curve is apparent. Next, take No. 3, No. 2, and No. 1, in that order. If, however, No. 4 does not begin to come to curve with 220, it is because your 80 grinding wore something from the surface of your lap, in which case your lap will have to be trued up to your template.

Wash up your lap and place it in your lathe, using your taper mandrel. With a piece of emery paper polish the concave, and with your hand tool proceed to turn or scrape out that portion of the lap which is too high. Go lightly, as probably one or two thousandths of an inch are all that it is necessary to remove. If the polishing with emery cloth is omitted, you will be unable to make a hand tool cut the lap; a little fine Carborundum and

glass has become imbedded in the pores of the metal lap from grinding, and unless removed with emery paper, will spoil the edges of your tools in a fraction of a second.

When you think that you are trued up sufficiently, try a short wet with 220 on your No. 4 blank. If you have gone too far in truing up your lap your glass will be very likely to become too shallow, where before it was too deep, or vice versa. However, if fairly close, carry on and grind all four blanks. Examine each one carefully with your magnifying glass for pits which are deeper than the general surface. The center usually takes care of itself and it is the edges which need watching closely. When no more deep pits can be seen, wash up, change papers, and start on your next grade (F). This time, however, start your series with No. 1 and work through to No. 4.

Go through exactly the same procedure as outlined above, truing up your lap if needed. Watch carefully for large pits and scratches. The latter usually mean that you have not been careful in cleaning up. Do not let your laps run dry, and do not use too much pressure—scratches will surely result. Run your spindle on slow speed and true, easily polished surfaces should result. When you feel satisfied that your F surfaces are as good as possible, wash up carefully, spread clean papers and change to 600 Carborundum.

The curves on your lens must be truly spherical and must be an exact fit with your templates. If they are not it will be an impossibility to make them take a good polish later on. True up your laps, by turning, as was done with the coarser grades, by grinding together under power or by grinding together by hand. This last method is not as fast as machine grinding but will, with patience, assure you of a good fit. Take the laps one in each hand and, with a little F Carborundum and water, rotate one on the other, first one hand then the other. It is slow and hard on the fingers. If you will take time to make up a couple of thimbles to fit your lap threads, it will be much easier on your fingers. Procure a couple of ⅝″ standard nuts and turn the outside to the shape shown in Figure 18.

Starting with No. 4 blank, proceed with No. 600 Carborundum until no pits whatever show on your surfaces. Do not over-grind with 600, as it is easy to get away from your curve. Take short wets and be very sure to keep things wet.

Wash up thoroughly, change papers, and gage carefully. Make a thick slurry of 6F emery and water, about half as fluid as cream, dab a little on your lap and some on the glass blank, and run until almost dry. Do not press hard or scratches will result. Do this with fresh portions of emery three or four times. Wash and examine closely. The surface should be almost satiny and if you used brass for your laps it will show a blackish sheen in the center. Glass, fine ground on cast iron laps, will not have this semi-polished appearance but under the microscope it shows just as fine a grain as a surface which has been finished on brass.

Polishing: Clean and wash up your grinding stand, bench, hands, laps, and everything else that might have a speck of Carborundum on it.

Procure a small wide-mouthed jar—one with a good wide base so that it will not be easily upset—clean it very thoroughly and mix in it two or three teaspoonfuls of rouge with water. Your mixture should be rather thicker than cream—in fact, it should be of such consistency that a drop will run with difficulty on a vertical glass plate. Procure a piece of sheet rubber (1/8" red sheet packing) 1" larger than the mouth of the jar, push the handle of

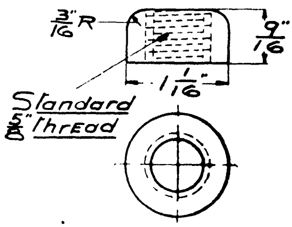


FIGURE 18
Steel thimble.

a 1/8" round camel's hair brush through the center of the piece of rubber and you have as clean and convenient a cover and dauber as you can get. Melt—do not boil—a small piece (1 oz.) of your pitch, strain through two thicknesses of cheesecloth into a clean can. Continue heating until a cooled drop can scarcely be dented with your finger nail. Get your pitch far harder than you would use for mirror polishing. Your pressures and friction are far greater in lens making, and hard pitch is a necessity. Warm your lap just enough to dispel the small droplets of moisture which show on its cool surface when held in an open flame, wipe dry and pour four or five drops of hot, liquid pitch into the center of the concave.

Paint one of your fine-ground blanks with a little of your rouge mixture and at once press it directly on the warm pitch. Work the glass around so that the resultant pitch lap is perhaps 1/32" thick. Thick laps (1/8" or so) get out of shape very easily. If your pitch hardens before you can press it out properly, hold the lap over the open flame for a few seconds. Put more rouge on your glass and press until your pitch coat is evenly spread over the concave of your lap. This operation can also be performed with the lap running in your spindle. Cool the lap off thoroughly under the tap and screw into your spindle.

Speed up your machine to 400 or 500 r.p.m. and with the sharp point of your pocket knife trim down the pitch lap to about 3/4" in diameter. Use plenty of water while doing this. Also cut out a small circle from the center of the lap, 1/8" to 3/16" in diameter. Cut clear through the pitch, down to the metal of the lap. Also cut two or three circular grooves between this center hole and the edge. Wash up thoroughly. Paint your fine-ground blank with a good coat of rouge and, with your spindle running at 400 or 500 r.p.m., press the glass firmly on the lap. Probably it will squeal and chatter for a few seconds. Press down fairly hard. Your lap will warm up

some and, in so doing, the pitch will flow to the exact curve of the glass. The whole thing—lap and glass—must, however, be kept wet. On no account allow it to dry off.

By the end of this first short run your glass should show a very distinct semi-polish, more noticeable in the center than on the edge. If your polish does not start in the center, something is very seriously wrong with your curve and you might as well go back to 600 or even to F Carborundum and correct your curve. A lens which polishes evenly from the center (I do not mean a small, sharply defined, locally polished spot in the center of the lens but an evenly graduated polish starting in the center) will polish out quickly and give you a good lens. A lens which polishes at the edge first is absolutely hopeless; in fact it is next to impossible to finish polishing such a surface. I have worked for an hour trying every expedient I could think of to get such a lens to finish out, while the same lens, had it started to polish properly from the center, would have finished up in less than five minutes. Since experience is a great teacher, try such a surface yourself and you will, I think, be firmly convinced. We hope, however, that you will not run into this snag, and that your lens is coming along in good shape.

Keep the central hole open at all times, and renew the circular channels as they become closed up. Five minutes will easily bring your lens to a complete polish if everything is going right. Examine the dried and cleaned lens closely with your magnifier. Small pits are extremely hard to see—in fact it often happens that, after you have finished your second surface and are able to see through your glass, a multiplicity of fine pits can be seen on one surface or the other. Be thorough, giving the lens just a little more polish after you figure that it is all finished. By this I do not mean to over-polish—which, by the way, is even more fatal to performance than leaving a few pits. Over-polishing will distort your curve and so spoil your image.

It is possible and permissible to alter your lap, either making it larger or smaller, by opening the center hole or by cutting zones in your pitch, to contrive so that your polish will come up evenly. However, such doctoring of laps should be left until you have acquired a little more experience. If you run into trouble in polishing, 90 percent of the time your fine grinding and curve were at fault.

The following quotation from "Orford," one of the leading English opticians, explains the importance of polishing from the center out: "It has been seen that I always make the polishers to take in the center, and at first thought it seems that I am intentionally polishing the lens away from the curve; but if we look further into the subject, we shall see that to get a fine surface, we must proceed as stated. In a series of experiments I carried out some years ago, I tried all kinds of polishers and methods of polishing, carefully noting every effect the different methods had on a test image. I found that, where a surface had been polished seemingly level, it turned out very badly under test, and a surface polished from the edge was useless for showing a perfect image, while all lenses polished from the center invariably gave good results; so to the workmen it is always their aim to start polishing

from the center as levelly as they can. . . . So it is seen that the edges of the polisher when in full work, must cut nearly twice as fast as the center, and if we had started polishing levelly, it stands to reason that the curve when bright would have been totally different from what was intended."

Your lap should easily last long enough to polish all four of your blanks. If it does not, make up a fresh one and go ahead exactly as outlined above.

Flat Surfaces: Remove your blanks from their handles as follows: Cool thoroughly in water, place in the hollow of the left hand and, with a piece of metal, strike the handle a sharp blow about 1" from the lens. If this is

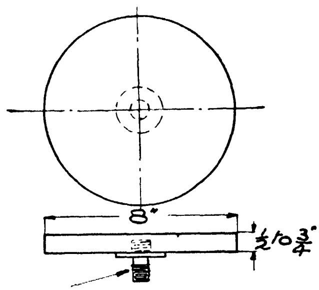


FIGURE 19

Flat lap, cast iron. Detail shown at arrow is the same as in Figure 17.

properly done the glass will come away clean from the tubing. Place in turpentine, to soak off any cement adhering to the glass.

Flat Laps: Procure a piece of cast iron about 8" in diameter and ½" to ¾" thick, chuck in the lathe, drill a hole ⅜" deep in the center and cut a ⅝" standard thread, so tight that a ⅝" stud will be tight when only three or four full threads are engaged. Take a light facing cut over the face of the cast iron, so that this side (the back) will run true with the axis of the stud. Relieve the threads on the stud close to the plate, cut the stud off to ¾" long, remove from the chuck and screw into your taper mandrel. Face up as accurately as possible and true the edge. Figure 19 shows the details of this lap.

The above directions are given for those who do not wish to go to the expense or trouble of having a proper flat lap casting made, or who happen to have a flat piece of cast iron on hand.

It is far better to finish the back of these larger laps with a standard taper socket. However, it entails making a pattern from which to have your casting made.

In making a pattern, allow about ⅝" per foot for shrinkage (for a finished diameter of 8", allow about 8⅜" to 8½" for shrink and finish, and have the boss made 1½" in diameter, so that you will have plenty to clean up on. Make a fillet around this boss of ample dimensions, say ⅜" or even ½" radius). Ask your foundryman to pour this casting with the face down—

this will help to eliminate sand and blow holes in the face. These, when using the lap in fine grinding, serve to hold grit and perhaps cause scratches.

A word here will not be amiss regarding the grade of iron used in your laps. A fine, even-grained, soft iron that is free from hard and soft spots is of prime importance—nothing is more exasperating than to have a lap practically finished, and then run into a sand hole or a hard spot.

Several years ago, in the practice of my profession, I had occasion to do considerable work with cast irons, and came across a specially heat treated iron called "Meehanite." This iron is absolutely free from hard or soft spots, and machines beautifully. It must be specified in ordering: "as soft

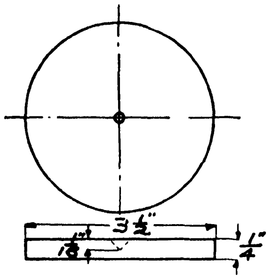


FIGURE 20
3½" runner, brass or cast iron.

as possible"; and it is wise to give the founder a line on the specific use to which the material is to be put.

The U. S. agents are J. S. Morrison & Co., Oliver Building, Pittsburgh, Pa., who will put you in touch with the nearest foundry who have the local agency in your vicinity. Meehanite costs 15 cents to 20 cents per pound in small lots, as against 6 cents to 8 cents for common cast iron, but is well worth the extra few pennies. [Prices as of 1935.—*Ed.*]

Next, make a flat runner. Face and edge a piece of cast iron to 3½" diameter. With a sharp-pointed tool turn a small conical hole in the center to a depth of 1/16". Cut off so that your piece is ¼" thick. Make three or four of these runners. Figure 20.

Screw your flat lap in your spindle, run it at 100 r.p.m., place a little 220 Carborundum and water on it and, taking your first blank between your finger and thumb, proceed to grind the flat side. With your double-ended brass calipers gage the center frequently until the thickness is within 0.05" of your finished dimension (in this case .1875"). The amount to leave varies with the size of lens and with your dexterity of manipulation. Keep an accurate record of the thicknesses of your blanks at this stage and after they are polished. In this way only can you judge how much to leave for grinding and polishing.

A very handy gage for measuring can be made as follows: Cut a strip of brass or steel exactly 5" long and ½" wide at one end, and taper it to

a point at the other. File the edges smooth, and straighten as straight as possible (Figure 21). Mark off distinctly each quarter inch, making the half inch marks twice as long as the quarters. The gage marks will have a value of 0.025", and lesser measurements can be made by placing the calipers between marks.

Be careful to wash your blank each time the calipers are applied. Don't press them hard over the curved surface. Make all four blanks to the same thickness. This detail is important.

Carefully wash up the lens and place it flat side down on your asbestos pad. Warm so that your cement will flow quickly and easily over the polished surface. Do not get any on the flat surface—if you do, clean it

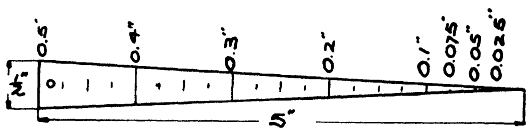


FIGURE 21
Brass gage, ½" x 5", 16-gage.

off. Next, warm up your 3½" runner and apply a liberal coat of cement to the plain side. Remove while still hot to a level place on your bench, and at once place your hot blanks—polished, convex side down—on the liquid cement. Arrange them symmetrically around the center. Allow them to cool, so that the runner can be inverted without the blanks dropping off. Place the whole thing, blanks down, on a piece of dry plate glass. Next take your bunsen, which should be connected with flexible tubing, and play the open flame directly on top of the runner. The cement will soften up and the glass blanks will level themselves on the plate glass. Do not get things so hot that the cement will run all over everything—just hot enough so that the blanks can adjust themselves in the same plane. Allow to cool.

Cut or break a number of fragments of the same kind of glass as you used for the blanks and place them over your burner—get them good and hot. By this time your runner should be set. Take the hot pieces of glass and drop them, flat side down, in the spaces between and around your blanks. Press lightly on each one, so that their under surfaces will be in contact with the runner and their upper surfaces fairly level, although quite a bit higher than the flat surfaces of your blanks.

Before I start to set a runner, as outlined above, I usually place my blanks and pieces in a symmetrical arrangement on an empty runner. In this way I can get a better idea of the shape of the pieces needed. Figure 22 shows a mounted runner—the main idea is to get the built-up surface as nearly continuous as possible, having at the same time some glass outside the outer edges of the blanks. If this precaution is not taken, the finished flat surfaces will show a decided turn-down in those portions which were adjacent to the periphery of the runner.

With the flat lap on the spindle running at 100 r.p.m., take the runner and carefully grind down the surface of the small filler pieces to the same level as your blanks. Use your calipers on the pieces around the edge, getting the same measurements from their surface to the back of the runner. No. 220 Carborundum will cut fast, take care so that you don't overdo things. When all seems level, wash up the runner, place a drop of oil in the hole in the back and, with the pin bar horizontal and the pin vertical, allow the runner to spin for a few seconds on the lap. Do not allow it to pass over

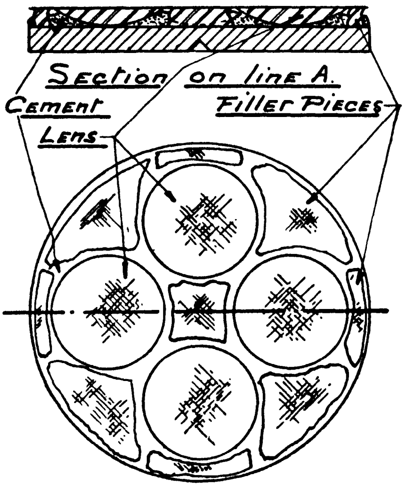


FIGURE 22

3½" mounted runner.

the center or edge of the lap. This spinning with 220 is not essential—it is simply done to insure a level surface to start with.

Wash up thoroughly, place clean papers, and give a short wet with F Carborundum. Thirty to sixty seconds should serve to take out your 220 pits. Examine the edges—the center will take care of itself. When no more pits can be seen, wash up carefully, change papers on your bench, and proceed with 600. Do not spin longer than necessary, as your lap is getting out of truth all the time and the less grinding you do on it the better. Watch the edge of your runner for pits—when all are gone, wash up again, place fresh papers on the bench, and change over to 6F emery. Run three or four wets of this, allowing the lap to become fairly dry between each wet, in this way the individual particles of emery are broken down thoroughly and a better surface will result than if the emery is kept too wet.

It is interesting to gage your runner between each grade of abrasive and see exactly how much is taken off by each.

Making the Flat Pitch Lap: Wash up your cast iron lap and warm it thoroughly. Melt and strain about one half of your remaining pitch and pour it into a clean tin pan large enough in diameter to take your lap. Heat up your pitch thoroughly and at once dip the hot lap, flat side down, into the pitch. Do this several times, endeavoring to get a thin, bubble-free coating on the face. Remove from the pan and, holding it vertical and rotating it slowly, play the open flame of the bunsen on the pitch surface. Most of the pitch will run off, and all the bubble holes should close. The ideal lap is perhaps 1/16" thick.

Place your lap on the bench to cool, making sure that it is level. If the surface has waves, pass your flame over it a few times and they will soon

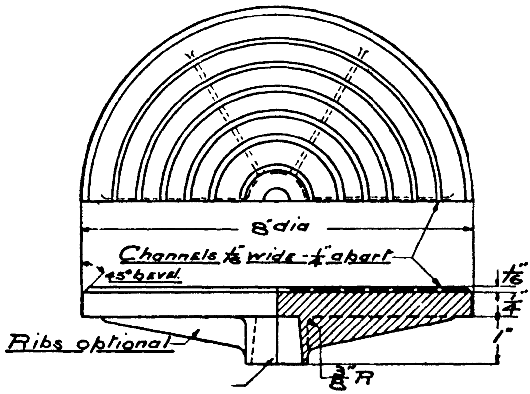


FIGURE 23

8" diameter flat pitch lap. The part indicated by bottom arrow calls for the same detail as in Figure 17.

level out. Allow it to cool slightly and, while waiting, clean up a piece of plate glass (old windshield) about a foot square and paint it over with rouge and water. Invert your lap on this rouged surface, work it back and forth, using plenty of elbow grease and keeping the lap revolving. If your pitch is fairly warm, one such working should serve to give you a good pitch surface. Small air bubbles 1/8" or so in diameter are rather desirable than otherwise, provided their distribution is fairly even over the whole surface. Figure 23.

Cool your lap thoroughly, place it in your spindle and, with your pocket knife, cut out a 1/2" hole in the center. Also cut channels, clear down to the iron, about 1/4" apart over the whole surface. Wash in cold water, scrubbing the surface lightly to remove any particles of loose pitch. Replace the lap in your spindle, coat thoroughly with rouge, place your runner in position with the pin in the oiled hole and then start your motor. Probably your runner will chatter on the rough lap for the first few revolutions, but

hold it down firmly and it will soon quiet down. It is well to have a cup of water handy to your rouge pot while polishing. Keep your lap thoroughly wet with rouge and water. Use only moderate pressure. Don't allow the runner to get set over the center of the lap—it may stick if it does.

Your polish should start in the center and work evenly to the edge, exactly as was the case on your convex surfaces. Polish clear out to the edge of the runner, wash up and examine with your lens. All pits, no matter how minute, should have disappeared.

Remove the lenses from the runner, by heating until the cement is perfectly liquid. Pick them off—don't slide them to the edge, or scratches may result. Do not attempt to wipe or scrape the cement off, but allow it to cool and place the lenses in turpentine a couple of hours or, better, over night, to soak. This will loosen all cement and grit. Wash with warm water and soap, rinse thoroughly, and wipe dry with soft tissue paper.

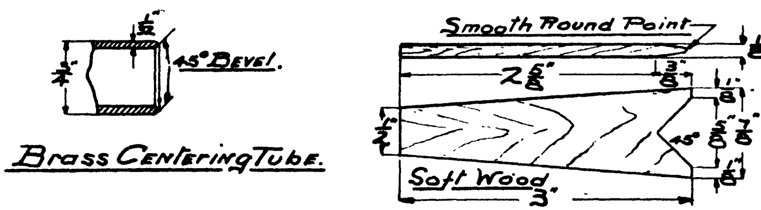


FIGURE 24

Brass centering tube and centering fork.

Centering: When the mechanical and optical axes of a lens coincide with each other, the lens is said to be centered. If these axes are not coincident the lens must be thicker at one point of the edge than it is at another. In other words your lens, taken as a whole, is prism-shaped—light rays will be resolved into a spectrum and very unpleasant effects will result when any bright body is viewed through such an uncentered lens. See Figure 57, *a*, page 69, "A.T.M."

Chuck a 2" length of ¾" brass tubing in your lathe, center it as accurately as possible and, with a pointed tool, chamfer the end both inside and out. The resultant edge should be quite thin and must run perfectly true. Figure 24, left.

With an alcohol lamp heat the end of the tubing and apply a thin coat of cement to the extreme edge. Warm up one of your blanks and apply cement to the convex side. Next, reheat the tubing and stick the cemented convex side as centrally as possible on to it. Then, with the lathe running at its slowest speed and with the alcohol lamp in one hand, warm the tubing. At the same time, and with a forked shaped piece of soft wood (Figure 24, right) in the other hand, gently move your blank on the tubing so that a reflection from its flat face will stay absolutely still. This job takes quite a bit of patience. Do not press so hard that you will stop the glass from revolving—to

do this will invite a scored ring on the convex side. Take lots of time. When perfectly centered, allow to cool.

The next step in centering—that of grinding the edge of the lens concentric with the axes—may be performed by using your tool holder and cross

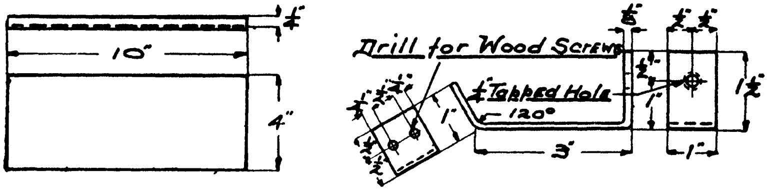


FIGURE 25

Left: 10" x 4" x ¼" tray. Right: Strut for centering dingbat.

feed saddle. However, it is rather messy, as Carborundum and water usually get over the lathe bed, etc. A better scheme is to cut a piece of ½" board 2" wider than the lathe bed and 12" or 15" long, and place this on the bed before you start centering your lens, cover it with paper and, in this way, protect the lathe. Also, should your lens slip, it is not so likely to get chipped.

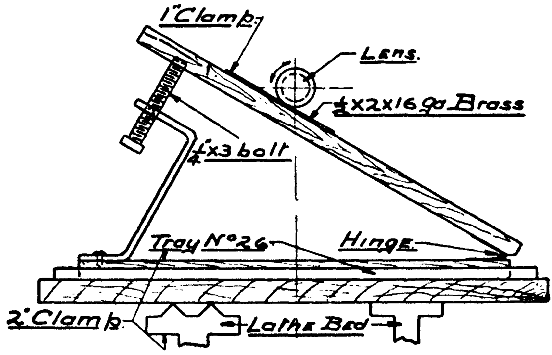


FIGURE 26

Centering gadget.

Make up a shallow tin dish 4" wide, 10" long, and ¼" high. Figure 25, left.

Take two pieces of wood 9" long, 1½" wide and ⅜" thick, and hinge them together at one end. Procure a strip of mild steel 1" wide and 7" long. Bend and drill it as shown in the same figure, at right. A ¼" bolt with 3" of thread and two ten-cent iron clamps complete the outfit.

Set up as shown in Figure 26, using one clamp to hold the outfit securely

to your lathe bed. The other clamp holds a small strip of 16- or 18-gage sheet brass, in place on the upper member. Adjust so that the strip is just in contact with the edge of your lens. Do not press hard. Apply 220 Carborundum (if your lens is away off center, use 80) and, revolving the lathe at its highest speed, proceed to grind the edge of the lens to your finished size. Stop grinding when the lens is about 0.01" larger than desired. Remove all of your rigging except the bottom ½" board, wash up and finish with a Carborundum slip. Put a slight bevel on each side, wash again, wipe dry and, with your alcohol lamp, warm the tubing. Remove the lens and cool. Place in turpentine to soak, wash in warm water and soap, dry on soft tissue paper—and your lens is completed.

Spinning: In most writings on lens making, the spinning method is given preference over the handled method outlined above. It is by far the best method for lenses of longer radius (either convex or concave), but with short radius convex lenses—1" or under—there are several inherent difficulties which cannot be surmounted. Chief of these is your inability to make a small radius convex lens travel away from the center of your lap—either the lens clings tightly or else lets go suddenly and flies off its runner. Concave lenses, no matter how short the radius, can be spun successfully and, if properly managed, as Porter says, "will leave the lap as a perfect surface of revolution."

Turn up two small runners 1" in diameter and ⅛" thick and cement to each of them a glass blank (same size as before—1¼" square). Grind these roughly on your wet Carborundum stone—one concave to your convex template and the other convex to your concave template. Place your convex lap in your spindle and, at 300 to 500 r.p.m., start and rough out your concave curve. It will save the curve of your lap if you make up a special rough lap and use it to take out the major portion of the glass. Go through the same steps with your 1" radius concave lap, and I think you will demonstrate to yourself how hard it is to make your convex blank behave itself. Your concave blank will go along fine—watch the curve closely, it is very easy to spin away from the template. Keep the pin pointing at a slight angle to the surface and keep it moving—spinning toward the edge of the lap deepens the center, while spinning with the glass nearer the center wears down its edges.

When working a double concave or a meniscus, make your runner to fit the curve to which it has to be cemented. For a convex surface your runner should have a slightly deeper curve than the glass—this gives a little more cement in the center. For a concave surface make the runner curve slightly shallower. This puts a thicker cushion of cement in the center.

In finishing an achromatic pair whose second and third surfaces are of the same curve, it is well to cement the first surface (work it first) to a runner, the back of which has been finished exactly the same as a lap—conical hole and screw complete. You can then spin your third surface on top. Your curves, with proper manipulation, will then run together. Achromatic combinations are given in the latter part of these notes.

Several lenses of rather flat curve may be run together as one unit. Porter has explained and illustrated the making of these, in "A.T.M.," in a very lucid manner.

MOUNTINGS—FIXTURES—JIGS

I have devised several jigs and fixtures for making eyepiece mountings. The time spent on these will be repaid several times over if you contemplate making even one full set of eyepieces.

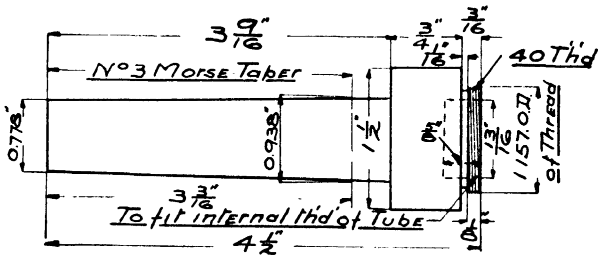


FIGURE 27

Steel mandrel.

Take a piece of steel 4½" long and 1½" in diameter and turn up a mandrel to fit your lathe spindle (Figure 27). Make the threaded part exactly 1.157" in diameter, and cut 40 threads per inch on it. This thread will fit the internal thread of your eyepiece tubing. The threads shown on

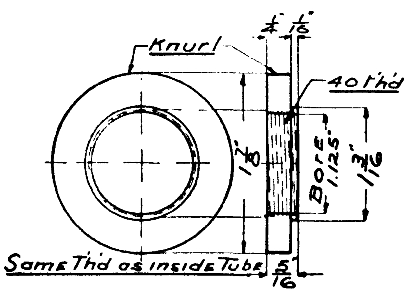


FIGURE 28

Steel ring.

pieces in Figures 27, 28, 29, 30 will be standards for all your future mountings, so take pains with them.

Turn up a steel ring, as shown in Figure 28—making your finishing face cuts with the ring screwed on your mandrel, thus insuring these faces being absolutely square.

Next, make the piece shown in Figure 29. The internal thread of this should accurately fit the mandrel, Figure 27. It will be best to face up this piece, bore and thread it, and then finish the external thread with the piece mounted on the Figure 27 mandrel. The external thread is the same as

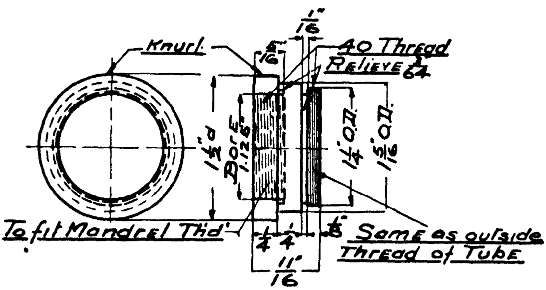


FIGURE 29

the outside threads on your eyepiece tube, and forms the gage to which to make the inside threads of your caps. Its diameter before threading should be 1.25″.

The mounting proper consists of four parts—the tube, the two lens rings, and the eye cap. All threads are 40 per inch. The tube is started as follows: Cut off 1½″ of your 1¼″ O.D. brass tube. Center this piece accurately

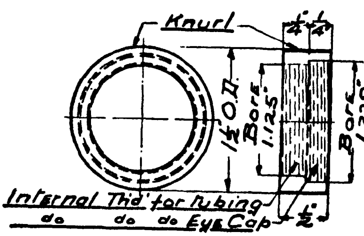


FIGURE 30
Thread gage.

in your lathe chuck, and face one end square. Cut 1⅜″ of thread inside, and ¼″ on the outside. Make sure that these threads are an easy fit with jigs 27 and 30 (Figure 31).

To make your lens rings, chuck a piece of 1¼″ O.D. brass, several inches long, center drill the tail end, and run up your tail stock. Turn the outside to 1³⁄₁₆″ (as these rings will be standard and made to fit any ordinary lens, you may as well make up 10 or 12 of them at one setting). With your cut-off tool, cut into the bar to a depth of ⅜″, leaving ⁵⁄₃₂″ between cuts. (See Figure 32). This will leave your rings ⁵⁄₃₂″ wide and connected together in the center by a bar ½″, more or less, in diameter. Next, turn off each ring to

1.157″ for a distance of ⅛″, leaving $\frac{1}{32}$″ to the full diameter of $1\frac{3}{16}$″. Put a fine knurl on this narrow flange and thread the 1.157″ part (to fit your gage No. 28). Figure 32 shows four of these rings.

The 1.157″ is arrived at as follows: 1.125″ is the internal diameter of your tube. 0.032474 is the double depth of a 40 thread. Therefore, 1.125 + 0.032474

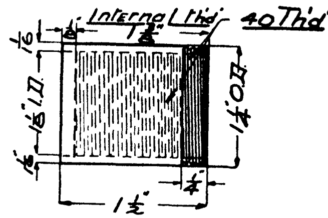


FIGURE 31
Eyepiece tube.

= the bottom diameter of your internal thread. Leave off the last three decimals and your thread will run nicely.

Eye-lens Caps: Chuck a piece of 1½″ round brass (Figure 33). If over 6″ long, use a steady rest. Face off the end. Bore to a depth of ¼″ and face the bottom of the bore. Cut a 40 thread inside to fit your standard on No. 29. Turn the outside to $1\frac{5}{16}$″ for a length of ¼″, partly cut off to a depth of ¼″ at $\frac{5}{16}$″ from the face, put a fine knurl on the $\frac{1}{16}$″ wide face, and finish cutting off. Details are given in Figure 33.

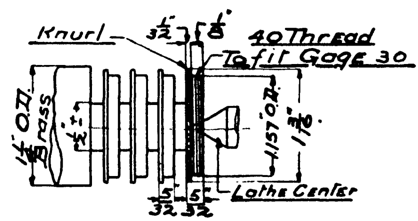


FIGURE 32
Brass lens rings.

Finishing and Fitting a Lens Ring to a Lens: Place mandrel No. 27 in your lathe spindle, screw jig No. 28 on the end, and into jig No. 28 screw one of your roughed brass rings. Your lens may be of any diameter up to about 1″. Drill and bore your ring to about .006″ smaller than the O.D. of the lens (this gives a shoulder .003″ all around for the lens to rest against). Counterbore to within $\frac{1}{32}$″ of the back of the ring .002″ larger than the O.D. of the lens—.001″ all around is about right. Next, with a sharp tool, turn out the face around the bore to a depth a little lower ($\frac{1}{64}$″) than the upper face of the lens will be when resting against its should--, leaving a

wall as thin as you possibly can (.002″ or less) standing up around the bore. Use a magnifying glass for this operation, and keep your tool sharp. Finish up with fine steel wool. Figure 34 shows a half-section and side elevation of a finished ring and lens for a Ramsden eyepiece. Reversing the lens in its setting and bevelling the 1/32″ shoulder will make this setting suitable for a Huygens field lens. Blacken and polish as detailed in a later paragraph.

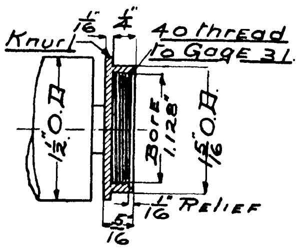


FIGURE 33
Brass eye cap.

Fastening the Lens in Its Ring: Procure a piece of 1/4″ round brass welding rod about 6″ long, file up the ends to a blunt point of about 1/32″ radius. Smooth up the ends very carefully. Run up your steady rest and adjust it so that it is just below the center of the lens ring. Place the cleaned lens in its setting and, holding it in place with the tip of one finger of the left hand, start the lathe. Run slow and, with the point of the brass rod which is held in the right hand, resting on the steady rest, very carefully burr over the thin wall of brass onto the lens. Do not press too hard. Take plenty of time, and gradually work the brass into shape. Try speeding up a little—

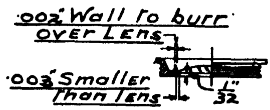


FIGURE 34
Lens ring.

sometimes the brass will turn over easier at speed than when running slower. Do not omit the final stage in blackening your mount; that is, heating as hot as possible and cooling under the tap. Brass is somewhat annealed by this treatment, whereas steel would be hardened. The brass wall or collar itself should be of such height that when burred over it just covers the bevel of the lens.

A very hard, smooth, steel point is recommended for this burring operation, also a tool with a small roller at the end. I have tried both, but have found that soft brass such as welding rods are made of, is less likely to tear the delicate brass wall.

The whole appearance of an otherwise perfect mount can be utterly spoiled by a poor job of burring, so take time and work carefully and slowly.

Finishing the Tube: First determine the separation required. This is given in the table (Figure 35, left) as 0.77″. The field lens is 0.20″ thick and the eye lens is 0.10″ thick, or a total of 1.07″ from plano- to plano-surface of the two lenses. Both rings should be bored and shouldered so that the plano-surface of the lens will be 1/32″ (0.03125″) below the outer flat surface of the ring. In other words, the total separation will equal the distance required between ring flanges. Place mandrel No. 27 in your lathe and screw your 1½″ long threaded brass tube on it; bore out to a diameter of 1 13/64″ for a distance of 0.43″. This will leave exactly 1.07″ of thread in the tube.

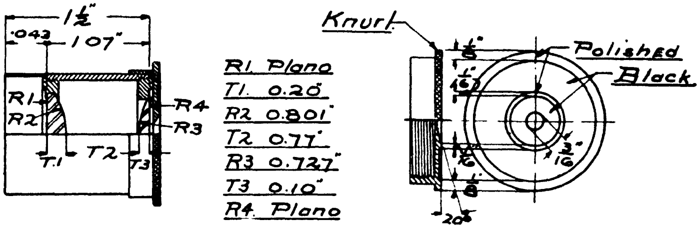


FIGURE 35
Left: Ramsden (Hastings), e.f.l. 1.015″. Right: Finished eye cap.

Make the inner shoulder square, so that the ring of the field lens will fit properly.

Remove from mandrel and screw in your rings and their lenses and look at a diffused light. If you can see any marks (dust, etc.) on the field lens your separation is too long, so replace the tube on the mandrel and turn out one or two threads. This allows the lenses to close up slightly—finally a point will be found when dust on the field lens cannot be seen. This is the best practical separation, although not correct theoretically.

Finishing the Eyepiece Cap; Screw jig No. 29 on your mandrel, and a roughed cap on the jig. Face up smooth. Drill a 3/16″ hole through the center. Chamfer the edges of this hole to 20°, clean up the eye hole so that it is exactly round and smooth, then turn a depression 1/64″ deep in the face, starting 1/8″ from the outer edge and to within 1/16″ of the chamfer around the central hole. Finish all over with fine steel wool. Remove any slight burr on the inside edge of the eye hole, and your mount is complete. A finished eye cap is shown in Figure 35, right.

Black oxidized finish is applied as follows: Take your smooth finished pieces (lens rings must of course be blackened prior to the insertion of the lenses) one at a time and dip them in a solution of 75 percent nitric acid and 25 percent water in which has been dissolved (with heat) as much copper wire as the acid will take up. Cool and decant into a glass jar and cover. Keep a few pieces of copper wire in your solution all the time. Dip the piece

in your solution, and then hold it in the bunsen flame (turn on all the air, in order to keep the flame oxidizing). The piece will dry up, turn green, and finally black. Immerse it a second time at once, while still very hot, in your copper nitrate solution. Heat up again. Repeat at least four times to get a good coat. After the last heating cool under the tap and wipe dry.

Procure some powdered graphite (soft pencil or an old soft carbon brush). Mix with a little machine oil and, with a rag, rub some of the mixture all over the piece—especially the threads. Screw on the proper jigs and, with the lathe running fast, polish lightly with a dry, soft rag. The eye caps are finished black all over; then, holding a piece of fine emery paper on a flat wood block against the face, polish a ring at the outer edge 1/8" wide and another 1/16" wide around the eye hole bevel. Only the outside of the tube is polished bright—all other parts should be thoroughly blacked.

Glass: Finding suitable glass for small eyepiece lenses has always been quite a bugaboo to the amateur. Rolled, annealed plate glass, as made by modern methods, is entirely suitable. Its index is that of ordinary crown. The Pittsburgh Plate Glass Company make a beautiful colorless glass which they have appropriately named "Crystallex." I have used it in making over 75 Ramsden and Huygen's eyepieces and have yet to find a flaw or striae of the minutest kind. Furthermore, the surface of this glass is so perfect that pieces 2" square will show practically perfect interference fringes when tested with an optical flat. Not all of this glass, of course, has such a perfect surface, but very little selection is needed to find pieces entirely suitable for diagonals and other small work.

Eyepiece Specifications: The following prescriptions for eyepieces have been collected from a number of sources—Bell, Porter, Orford, Conrady, Hastings, etc. I have made all of them at various times. Some perform rather better than others, but in general it may be said that for ordinary amateur use the Ramsden type is preferable to some of the more complicated ones. Hastings' solid oculars, especially his Type D ("A.T.M.," page 178, 3rd edition, 4th edition), give a small, clear field. However, they are very sensitive to slight variations from the set formulae, and are especially hard to center properly.

The stated radii and thicknesses read from the front of the field lens to the back of the eye lens in each case. The figures given are for an *e.f.l.* of 1", and should be divided or multiplied in order to increase or decrease the focal length. ("A.T.M.," page 71, 3rd and 4th editions). The diameter is dependent on the radius and the center thickness, and can be made anything desired, as can your edge thickness.

The crown and flint glass used in these eyepieces should, unless specifically noted, have the following approximate constants.

	V	D	C	F
Crown	63.6	1.5137	1.5113	1.5194
Flint	36.7	1.6164	1.6120	1.6288

The former can be procured up to .625" thick from the Pittsburgh Plate Glass Company, Pittsburgh, Pa., and the latter from Mr. L. D. Keller, 2344 N. 19th Street, Philadelphia, Pa.

However, as mentioned before, ordinary rolled, annealed plate will prove very satisfactory for any of the simpler lenses and eyepieces. The more complex ones, however, are the result of deep mathematical study and the constants specified should be adhered to as closely as possible.

In the following formulae, all convex surfaces are +, all concave surfaces are —, regardless of light ray impingement.

Ramsden

e.f.l.	1″	1.178″	1.015″
R_1	Plano	Plano	Plano
T_1	.20″	.18″	.2″
R_2	+.666″	+.625″	+.801″
T_2	.666″	.938″	.77″
R_3	+.666″	+.625″	+.727″
T_3	.10″	.09″	.10″
R_4	Plano	Plano	Plano

No stops or diaphram required.

Huygens

e.f.l.	0.941″	0.978″	2.58″
R_1	+1.00″	+1.10″	+2.00″
T_1	.20″	.19″	.30″
R_2	Plano	Plano	Plano
T_2	1.10″	1.20″	2.90″
R_3	+.40″	+.40″	+1.00″
T_3	.10″	.09″	.15″
R_4	Plano	Plano	Plano

Make the diameter of the stop the same as the outside diameter of the eye lens and adjust until the edges are sharp. The last example is from Conrady.

Kellner

			N/d	V	Bausch & Lomb No.
e.f.l.	0.75″				
R_1	Plano	Eye lens —	1.5744	57.7	110-1—Crown
T_1	.05				
R_2	+.318				
T_2	.15—R_2 and R_3 cemented				
R_3	+.318	Eye lens —	1.6041	37.8	200-3—Flint
R_4	+.524				
T_3	.75				

R_5	$-.70$	Field lens —	1.517	63	20-3—Crown
T_4	$.12$				
R_6	Plano				

Hastings Three Lens Ocular. *e.f.l.* 1.00″

			N/d	V	Bausch & Lomb No.
Dense Barium Crown.			1.5725″	56.8″	110-1
Light Flint			1.5795″	41.0″	190-3

R_1	$+.735''$	diameter	.448″	—Flint
R_2	$-.276''$			
T_1	$.06''$			
Cemented				
R_3	$+.276''$		.400″	—Crown
R_4	$+.279''$			
T_2	$.196''$			
Cemented				
R_5	$-.279''$		.448″	—Flint
R_6	$+.745''$			
T_3	$.056''$			

Has a small field and beautiful definition.

Steinheil Monocentric (original specification), *e.f.l.* 25mm.

R_1	+19.78 mm.			
R_2	± 7.98 mm.	T_1	22.12	diameter 11.00 mm.
R_3	± 7.98 mm.	T_2	4.24	
R_4	+19.78 mm.	T_3	22.12	

Steinheil Monocentric (later specification), *e.f.l.* 1″

R_1	$+.775''$	Flint	diameter 0.8″ tapered to 0.4″
T_1	$.492''$		
R_2	$\pm.282''$	Crown	diameter 0.4″
T_2	$.507''$		
R_3	$\pm.226''$		
T_3	$.283''$	Flint	diameter 0.4″
R_4	$+.510''$		

The glass specified for both of the above is:

	N/d	N/h	V
Crown	1.51705	1.52767	64.0
Flint	1.61358	1.63207	37.0

Achromatic	*e.f.l.* 1″		
R_1	−6.15″		
T_1	.035″	Field lens—is a very thin meniscus.	
R_2	+1.250″	Crown glass. Diameter 0.5″	
Separation	0.746		
R_3	Plano	Flint glass	diameter .3125″ (eye lens)
R_4	−.525″	Flint glass	diameter .3125″ (eye lens)
		cemented	diameter .3125″ (eye lens)
R_2	+ .525″	Crown glass	diameter .3125″ (eye lens)
R_1	+ .525″	Crown glass	diameter .3125″ (eye lens)

Same glass as used for the above Steinheil monocentric. The original source of this particular formula is unknown. I have made a number for use with telescopic rifle sights and they work well.

Solid Ocular. Original made by Brashear and now is in possession of Mr. C. Goin, of Pittsburgh, Pa.

e.f.l.	0.75″	
		diameter at large end 0.736″
R_1	0.5″	
		diameter at small end 0.446″
R_2	0.3″	
T_1	1.28″	

This ocular has a diaphram groove (à-la-Coddington) cut into the glass. This has a diameter of 0.3″ at the bottom of the groove, which is located 0.35″ back of the front of the field lens face.

The following table gives the dimensions of Huygens and Ramsden eyepieces, for an *e.f.l.* or 1″. The values given may be varied to suit particular conditions. Note the variations of Conrady's Huygenian as given above. In general they will be found very suitable to general needs.

	Huygens	*Ramsden*
e.f.l.	1.00″	1.00″
Focus of field lens	1.50″	1.25″
Radius of field lens	.75″	.625″
Diameter of field lens	1.00″	.75″
Focus of eye lens	.75″	1.25″
Radius of eye lens	.375″	.625″
Diameter of eye lens	.375″	.375″
Separation of lenses	1.125±	.832″
Diameter of stop	.375	

I would strongly advise the beginner to make a number of simple lenses, both bi-convex and plano-convex, before tackling the Coddington (Hastings) type. I have a whole set of solid uncapped eyepieces of this type, from 1" to $\frac{1}{10}$" F. The last has an R_2 of 0.04" and a total length of 0.16". Try one of these small lenses as an exercise in lens making. If it turns out well, you should apply for full membership in the nearest Pollyanna Club—you surely deserve it.

If any amateur who reads this article has any criticism or question to ask, please do not hesitate to do so—it has been written with the sole thought of arousing interest in this particular branch of telescope making. Probably

Plan and elevation of the author. Left: This shows the handle shown in Figure 11. Right: Looking for scratches. [*Mr. Clark is Chief Engineer of the American Zinc and Chemical Co.—Ed.*]

some of you have evolved formulae for eyepieces, microscope objectives, or other optical apparatus which you are not in a position to develop yourselves or to have developed by professional opticians. I should be only too glad to lend what small skill I have to the furtherance of such development, and to add in some small measure to the splendid work already accomplished by amateurs in the past. Letters may be sent to the author at Langeloth, Pennsylvania.

I am deeply grateful to Messrs. Ingalls, Porter, Sheib, and Scanlon, for their interest and correction of the original manuscript.—*Langeloth, Pa. (Box 112), August 1, 1935.*

A Postscript on Objectives: Those who wish to make a finder objective will be sure of good results if the method of Donald Sharp ("A.T.M.," 4th edition, page 311) is followed carefully. In testing, the following set-up is used. Make your lens and its mount, and set up half way between the knife-edge and the pinhole, which should be separated by four times the focal length of the lens. The shadows are interpreted as with a mirror

Your final shadows should look exactly the same as those of a spherical mirror, for good results. Watch for a turned edge—it will spoil your image. If you have a flat, follow Ellison's auto-collimation test.

I have made a number of finder objectives, from 8″ to 20″ F and from 1½″ to 2½″ diameter, by the above method, with good results.

The correct centering of object glasses over 2″ in diameter is quite a problem for the average amateur. If undertaken in the manner so lucidly explained for small lenses by Porter ("A.T.M.," 4th ed., page 67), serious troubles are sure to develop at the outset.

The chief difficulty encountered with Porter's method, when applied to larger lenses, is due primarily to their greater weight. While the pitch is

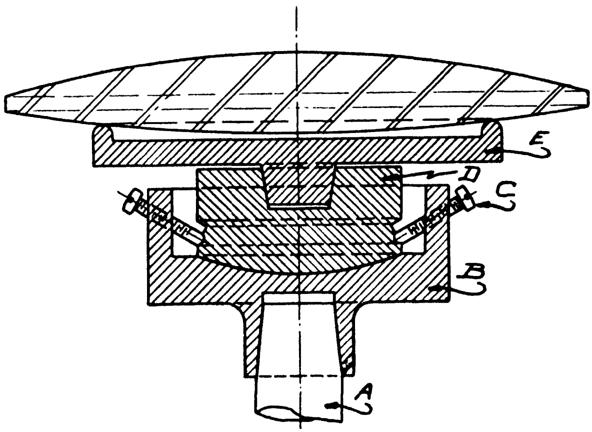


FIGURE 36
Brashear's method.

still warm, there is a decided tendency for the glass to slip from its correct position on the brass tubing. Extra pressure has to be used on the polished surface of the lens in order to overcome this, with the result that slicks and small scratches very often result.

The obvious remedy for this condition is to make the axis of the brass centering tube vertical instead of horizontal. If, however, this is done, it is almost impossible to warm the tube without grave danger of cracking the lens.

I have employed the following method. The accompanying illustration (Figure 36) will help to make things clear.

A vertical spindle *A*, which must run true, is required. The chuck *B* has four screws tapped into it 90° apart and at an angle of 30° from the horizontal. The top surface of B is finished with a shallow seat of about 3″ radius. Piece *D* has a corresponding rounded surface of the same radius. The upper surface of *D* should have a tapered hole to fit the tapered stub

on the underside of lens holder *E*. This lens holder should have an outside diameter about 2″ less than the lens which is being centered. The annular ring on its upper side should be finished with a rounded section, so that line contact only, will be made between it and the lens.

The following method of using this rig will be found convenient. Assemble the various pieces as shown in the sketch, and by means of the four screws bring the top ring of *E* as nearly true as possible. The final truing is best accomplished by taking a fine cut, preferably with a grinder, on the apex of the ring. Remove the lens holder and warm it. Run a little pitch around the top of the ring, place the already warmed and turpentined lens on it, and press into firm contact. Replace the lens holder on the chuck and, by means of a reflected light, center the lens as closely as possible. If, as usually happens, the pitch hardens before the job is perfect, it is a simple matter to warm the underside of the lens holder, and continue the adjustment until no further adjustment can be made.

The actual grinding of the edge of the lens is best accomplished by means of a soft iron disk, running at fairly high speed and fed with Carbo and water, the side of the disk, and not the edge being placed in contact with the edge of the lens. The lens should be revolved at such speed, that the Carbo will not be thrown off by the centrifugal action. Failing a grinding rig, a piece of brass or hoop iron, bent to a partial circle, will make a very satisfactory substitute.

Ellison's method of "miking" the edge thickness leaves much to be desired. Both surfaces of the lens are curved, and great difficulty will be experienced in placing the tables of the micrometer at exactly the same radial distance around the lens. Five ten thousandths (0.0005″) of an inch difference in edge thickness is rather more than the difference between a first class lens and a mediocre one. Such an error can easily be made, especially by one who is none too well versed in the use of a "mike."

That there are differences of opinion regarding this operation is evinced by the "discussion" between Ellison and Fecker ("A.T.M.," 4th ed., page 459). Far be it from me even to question the accuracy of the former's methods; so, as an alternative I submit the foregoing scheme, which I feel sure will be found more nearly fool-proof in the hands of the average amateur.—*R.E.C.*

Oculars at Small Cost

By W. T. Patterson, R. O.
Guelph, Ontario, Canada

Having read in "A.T.M." several articles on oculars, and noting that the tools required included an expensive screw-cutting lathe, I decided, in the interest of some amateurs (myself included) who are not fortunate enough to own such a machine, to seek some other way out of the difficulty. Figure 1 shows the details.

The main thing was to find a source of ready-made parts. Accordingly, I proceeded to shop about for suitable materials which could be obtained at

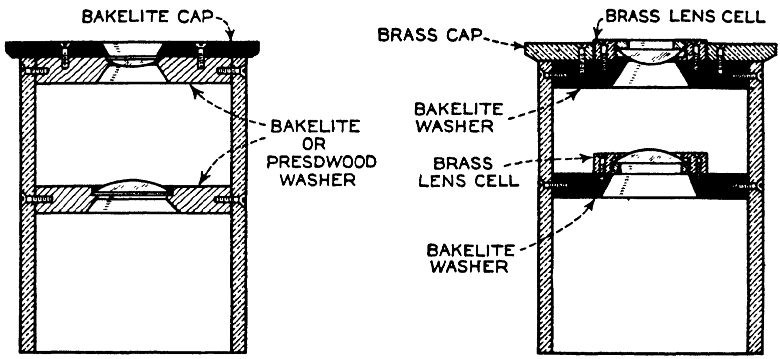


Figure 1

A simple eyepiece and another with removable lens cells.

small cost, and the following is a list and description of parts obtained. They served the purpose very well.

(1) Bronze car bushings marked "C. G. B." These have an outside diameter of 1¼″, the standard size for astronomical use. They were obtained at a garage for 8 cents apiece.

Another and perhaps better substitute, since tried, may be obtained from any electrical and plumbing contractor, and consists of nickeled cuttings from brass pipe. Four 2″ lengths, 1¼″ outside diameter, were obtained for the sum of 10 cents.

(2) Sheet Bakelite, salvaged from a homemade radio of the old type, which can be obtained from most any "ham" or at radio shops, which are glad to get rid of it.

Masonite Presdwood may also be used, by giving it more solid body with an overnight soaking in shellac, but I found Bakelite better, as it holds screws more firmly and makes a neater job.

(3) Plano-convex lenses of short focal lengths, 1″ or less, may be obtained from pocket magnifiers, etc. Those used in most of the oculars

described here were obtained from a cheap telescope and microscope of Japanese make, obtainable for about a dollar each in many optical stores throughout the country, from the Orient Import Co., Detroit, Mich. The objective lenses of the microscope were used for one ocular, and the erecting eyepiece of the telescope yielded four lenses for two others. These lenses are of good quality and are mounted in brass cells, which simplifies the work of assembling.

Lenses can be obtained from view finders taken from old cameras, field glasses etc., if one is fortunate enough to obtain them. The alternative is to grind and polish your own lenses. I have used blanks cut from flat spectacle lenses, the plane side of which is already finished and, being of good quality optical glass, these will produce good lenses.

(4) A few dozen rimless spectacle screws and a tap of the same size. These may be obtained from any optician, and were found excellent in assembling the parts. A No. 60 twist drill is the proper size for use with these screws.

A few other tools are needed as well, which most mechanics have on hand. These consist of a few small drills, a sharp knife, and files.

The total cost of materials used in four oculars is as follows:

bushings	$ .32
Bakelite	.00
pocket magnifier	1.00—double aplanat (2 lenses)
telescope	1.00—using eyepiece lenses alone
microscope	1.00—using objectives lenses alone
screws and tap	.50

Total— $3.82, or about 83 cents apiece for each ocular. The eyepiece of the microscope can also be used to make a negative (Huygens) ocular, but the quality of these was found to be a little uncertain. However, it is good enough for experimenting and will give fairly good results.

Now for the actual work. The bushings are rolled from sheet brass, consequently they have a seam down one side. This seam should be soldered, in order to prevent expansion. First, the seam is opened slightly with a knife blade. The bushing is then heated over a gas flame and some solder is flowed into the opening. The tube is then held in the hand and filed down to the exact size, using a broad, flat file and giving it a circular motion as the tube is rotated.

Any high spots can be removed and a perfectly round tube produced, with a little practice. Be sure not to file off too much, but just sufficient to bring the diameter back to 1¼", so that the ocular tube will fit snugly into the adapter tube of the telescope.

For truing up the ends of the bushing a strip of straight cut paper is rolled around it in such a way that one edge of the paper is straight in line with the underlying edges. The ends are then filed square, using the paper as a guide. Repeat the process with the other end.

I have since used seamless brass pipe, which has a better finish and

eliminates the necessity of soldering. Four tubes should be prepared for our set. Next, cut eight disks of Bakelite or treated Presdwood. These are cut slightly oversize and filed down perfectly round, so that they fit tightly in the tubes. The bright surface of the Bakelite is changed to a dull black by a few strokes with a file or sandpaper, and the bushing is blackened inside by immersing it in copper nitrate solution and heating, as described in "A.T.M."

In the exact center of each disk a hole is cut, and enlarged with a knife or scraper until the edges clear the full aperture of the lens or, if unmounted lenses are to be inserted directly into the disks, the hole is made the same size and countersunk.

The focal length of the lenses is next checked, using the simple instrument to be described later. The lenses are then mounted in or on the disks, and these are placed in the tube the correct distance apart.

Here are the calculations for a positive or Ramsden ocular.

(a) Image focused in front of combination.

(b) Two plano-convex lenses of equal focal length, spaced apart ⅔ focal length of each lens—equivalent to single lenses of ¾ focal length of each lens.

(c) Convex sides face each other.

For example:

Take two plano-convex lenses, f.l. ½″ each.

Spacing $= \frac{2}{3} \times \frac{1}{2}'' = \frac{1}{3}''$.

Equivalent focal length of combination $= \frac{3}{4} \times \frac{1}{2}'' = \frac{3}{8}''$.

For the negative or Huygens ocular we have:

(a) Image focused between field and eye lens.

(b) 2 Plano-convex lenses: Eye lens L_1, field lens L_2. Focal length $L_1 : L_2 = 1:3$

(c) Spacing $= FL(L_1) + FL(L_2) = \frac{1}{2}$ sum focal length—equivalent to single lens of ½ focal length of field lens.

(d) Convex sides both turned away from eye:

For example: F eye lens $= \frac{1}{2}''$. F field lens $= 1\frac{1}{2}''$. Spacing $= \dfrac{\frac{1}{2}'' + \frac{3}{2}''}{2} = 1''$

Equivalent focal length of combination $\dfrac{1\frac{1}{2}''}{2} = \frac{3}{4}''$

The centering of small lenses is a simple matter, for any spherical lens which is perfectly circular and of equal thickness around the edge is bound to be exactly centered; so all that is necessary is to check the edge, whereupon any slight variation will be noticed and remedied by grinding a little off the side which is thinnest.

Care should be taken to have the plane of each lens exactly parallel with that of the other, as a slight tipping will produce an uneven focus.

Having completed our calculations, the disks are then fastened in the tube by means of the spectacle screws. Three or four equally spaced holes are drilled around the circumference of the tube at the location of the disks,

and about ¼″ into the edges of the disks themselves. The small tap is then used and the screws turned in.

A word of caution regarding drilling and tapping Bakelite—do not force the drill, but proceed slowly and remove and clean it after each few turns, as Bakelite clogs the grooves. Running the drill into a cake of soap will lubricate it and reduce friction.

The lenses, already mounted in a brass call or washer, are now fastened to the Bakelite disks by means of three or four equally spaced screws, care being taken to center them exactly.

A cap disk may then be cut from sheet brass or Bakelite slightly larger than the 1¼″ tube diameter (1½″ is about right) and the center is cut out so

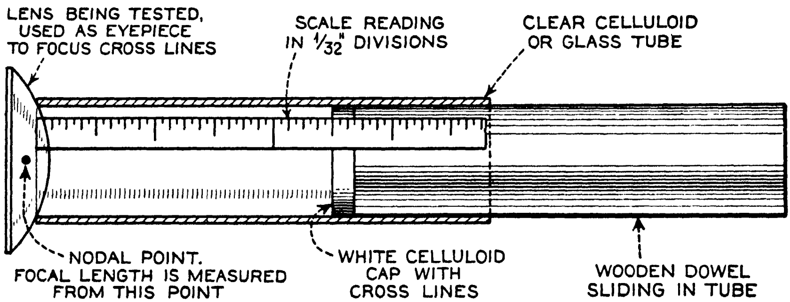


FIGURE 2

that it will fit down over the eye lens cell. The cap disk is then fastened to the eye lens disk with several screws, and the ocular is completed.

The first ocular I made turned out so successfully that I decided to make a set, and I now have six.

The Ramsden oculars produced are as follows:

(a) High power of ¼″ focal length, using the objective lenses from the dollar microscope.

(b) Medium high power of ⅓″ focal length, using the eye lenses from the dollar telescope.

(c) Medium low power of ½″ focal length, using the erecting lenses of the same telescope as in (b).

(d) Low power of ⅞″ focal length, using lenses from a pocket magnifier.

These oculars were first tried out on a standard French make of telescope, draw tube type, of 25× magnification, and gave excellent definition up to the highest power.

The oculars listed give magnifications as follows: 28×, 50×, 75×, and 100×.

They were later used with a 3″ objective of 42″ focal length, and gave up to 126× magnification with perfect definition, but slight achromatism with

168×. However, this was due to the object glass being corrected for lower powers.

Testing Small Eyepiece Lenses for Focal Length: Figure 2 shows a simple instrument for testing small eyepieces for focal length.

Probably the easiest way to measure lenses of long focal length is by focusing sunlight to a point. With short focus lenses one will at once meet with difficulties, since accurate measurement is then impossible.

Accordingly, this simple instrument was designed, and will give the focus of small lenses accurately to within $1/32''$.

A small tube of Celluloid or glass is used, bearing a small scale graduated as shown, and a small round stick of wood is made to slide up or down snugly in the tube.

On the upper end of the stick a small, round cap of white Celluloid is cemented, bearing a number of fine cross lines scratched on its surface and filled in with india ink.

To measure a lens, simply place it on the upper end of the tube, as if it were an eyepiece, and slide the stick up or down until a sharp focus of the cross-lines is obtained.

The reading is made direct from the scale at the point to which the stick has been moved. One half of the thickness of the lens is subtracted from this reading.

By means of this instrument a quantity of assorted lenses can be matched in a few minutes and paired off for use in eyepieces.—*108 Wyndham Street.*

The Refractor—Metal Parts and Mounting

By D. Everett Taylor
Willimantic, Connecticut

When the amateur looks through or into the telescope which his craftsmanship has created, and beholds the Moon, Saturn, Jupiter or some other wonder of the heavens, he experiences, in most cases, a justifiable sense of pride and satisfaction. His investment in time, effort, and expense, becomes paltry, automatically forgotten, and he will probably confess that the work of construction has been of absorbing interest throughout. By sharing the pleasure and enjoyment which a telescope will give, he can leaven his whole neighborhood, including other friendly contacts, with enthusiasm and interest in the stars.

A good telescope is decidedly worth while. The aim of this chapter is to aid the amateur with a description written in considerable detail, of the building of a refracting telescope similar to the instrument illustrated in Figure 1. This will not include comment on, or directions for making an eyepiece or the highly important objective. Information on those subjects will be found elsewhere in this book.

For the early history of the telescope, its development, and a comparison of the refractor and reflector, the reader is referred to "The Telescope" by Bell. A brief digression from our subject may, however, be permitted here, for the addition of the following running quotations, each of which carries its own punch of information: "The refractor is practically fool proof . . . "because of the great convenience of its use and maintainance . . . "little affected by changes in temperature. . . . You can, by using a star diagonal on a refractor, cover any part of the heavens, while comfortably seated. . . . "Refractors are satisfactory for daytime use, because the eyepiece receives no light except that which comes through the lens." "The refractor can be made a thing of great beauty. . . ."

Much, much more could be said in praise of the refractor, but our digression is limited.

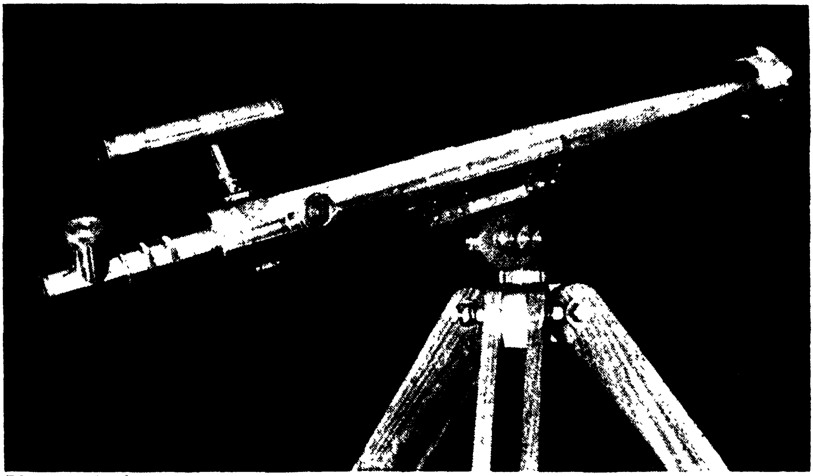
If the reader has a technical, mechanical turn of mind, and is possessed of inventive and creative ability, he may choose, after reading this article, to vary the design and procedure recommended. On the other hand, if he wishes to *follow* a definite programme, he will make no mistake in adopting the detailed directions found in this chapter. If these directions are accurately followed, the result should be a refractor (metal part) which is not alone precise and accurate in operation but good to look at, as well.

Size: When we come to the consideration of size for a proposed refractor, one general rule or saying can be laid down: namely, performance is of greater importance than size; also the well-known expression, "a good little one is much better than a poor big one." Fraunhofer, it is said, did most of his revolutionary work on the star spectra with a 1″ objective. Olcott says, "a three-inch refractor is ideal for the amateur." Hale says, "a four-inch refractor is all that can be desired for looking at the spectra of stars."

Kirkham says, "If I had it all to do over again, I would make a smaller refractor—four or four and a half inches."

The 60 mm. (2⅜″) refractor shown in Figure 1 is a highly satisfactory instrument with regard to size. The owner and builder of a 10″ reflector, while observing with it remarked, "I can see as much in this as in my 10″ reflector; my image is a tiny bit bigger, that is all."

Refractors up to 4″—possibly larger—can well be mounted on a tripod, if the latter has sufficient weight and solidity, and are easily portable. Refractors of 5″ aperture or more deserve, and should probably have, a permanent mounting of rock solidity, with a protective covering.



Photographs by the author

FIGURE 1

A 60 millimeter (2⅜″) refractor made, excepting the eyepiece, by the author.

So, in choosing the size which you wish to build, remember it is not size that is most important, but the quality of performance.

The following paragraph, culled from correspondence after the above was written, is added here because the comment is so authoritative and valuable that the beginner should have the information before he unwittingly falls into making decisions which he might later wish were different. This paragraph was written in a personal letter by a professional whose name is widely known and whose accomplishments in the field of telescope optics are much respected and admired—his name is withheld to save him any possible embarrassment because of his frankness, privately expressed.

"I would like to point out one thing," he writes, "which beginners overlook. A really fine 4-, 5-, or 6″ reflector will keep an intelligent person busy a full lifetime. It is much to be regretted that the fad for large

diameters has gone as far as it has. Astronomers and practiced observers will tell you that a good 3″ refractor will show you everything that an amateur will want to see. I can vouch for that, and perhaps you will be surprised to learn that the only telescope I have at present is a 1½″ refractor."

Some will possibly disagree with the above quotation and, if you do, it is your privilege, for in quoting it there is no thought of stepping on the toes of anyone, but only of giving the beginner an authoritative opinion on refractor sizes. Make your own decisions, and may success attend you.

Material: Brass has been so generally used for refractors up to, say, 5″ that it is the undisputed standard. While other materials have been used for the main tube, they will be found in general less desirable than brass. The amateur who makes his entire refractor of brass will not be disappointed. Brass tubing in a wide variety of sizes and gages is obtainable from dealers in tubing. Some sizes can be furnished in either yellow or red brass. Yellow brass for the entire job will be easy to obtain. Small tubing, such as telescoping draw tube 1¼″ to 1½″ in diameter, in red brass, is not listed in dealers' catalogs, therefore red brass should not be considered for the entire telescope. Yellow brass tubes with red brass trimmings make an impressive finished job, but if you adopt this combination be sure to instruct your foundry correctly, when castings are ordered, *i.e.* red brass for all trimmings.

If you patronize a foundry where virgin or new metals are used instead of scrap metal, you will get castings of better quality.

It is well to remember that plumbers carry in stock brass pipe in a variety of sizes, some of which is heavy-wall, and some thin. Uses for brass pipe will turn up as the work progresses. Stuffing box rings, as described in the text, can be made from heavy-wall brass pipe, with little waste of time or material. Some hardware stores carry brass rod in diameters from, say ⅜″ up to 1″, which is desirable stock from which to make small parts such as special screws and thumbscrew heads.

Cost: The price of brass tubes in lots of less than 20 pounds varies from 30 cents to over 40 cents per pound (1935), according to diameter and gage. Castings in brass are quoted at similar prices, with the same spread. The following were the costs for tubing and castings for the 3½″, 52½″ focus instrument shown in Figure 2. Tubing, $10 (main tube extra heavy—explained later in text). Castings, about $6. Top of tripod cast in german silver, very heavy in design, $4.50. Tripod legs with brass spacers, bolts, etc., say $3 to $4. Castings for an alt-azimuth mounting, similar to the mounting shown in Figure 1, will cost about $3. With clever planning and recourse to used material, which in many cases is just as good as new, the above costs can be greatly reduced. So, with a gross expenditure of approximately $50 for materials, including glass for the objective, it is possible to create a refractor of high quality, equal to an instrument which in the market would cost from, say, $350 up.

After reading the foregoing, as an introduction, the prospective builder

may have formed a definite idea as to what he wants his refractor to be in size and material. The discussion which follows presents practical directions for making a refractor—that is, the metal parts—of high quality.

Practical: Making working drawings is wisely the first practical move, followed by making or getting patterns for castings and ordering the main tube, and the telescoping tubing for the draw and focusing tubes. Here are two important points, which should not be forgotten when you figure the main tube requirements. If a refractor is to be used successfully for ter-

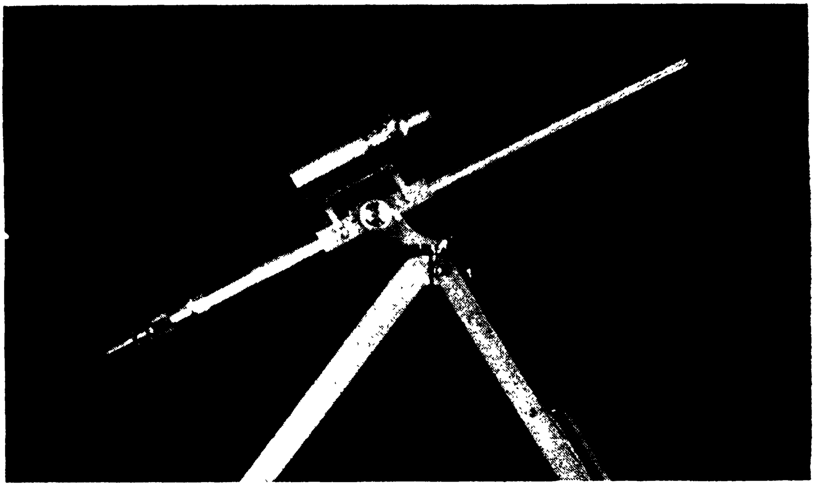


FIGURE 2

A 3½" refractor which was not completed until after the foregoing part of the chapter had been written. The photograph is included for the purpose of offering suggestions in design. The refractor has a 52½" focal length. Outside diameter of main tube 3¾". Overall length as shown, 54". The superimposed reflector has a 4¼" mirror, with a focus of 11" (f/2.58). The brass tube is 5" in diameter and 12½" long. The tripod legs were sawed from a heavy plank at the mill; the remainder of the work is by the author.

restrial observation, it requires a prism erecting system. A suitable Porro prism, in its mounting, will take about 4" of the cone of light. In other words, the prism shortens the operating focus about 4". Therefore, 4" of tube shortening must be allowed for when the length of the main tube is planned. That this point may be thoroughly understood, let it be again stated from another slant. Avoid making the main tube too long. When the focusing tube and draw tube are telescoped into the main tube to the shortest adjustment, the length of the whole assembly, from the objective to the eyepiece end of the draw tube, should be at least 5" shorter than the focal length of the objective—4" which the prism system will absorb, and 1"

for operation and use of high power eyepieces, thus making up the 5". A 6" allowance is not too much.

The second point, independent of the first or previous point, is: to the required length of any main tube, at this stage, add 1½" to the length. Shortly it will be explained how this extra length is to be cut off the main tube in the form of two rings or bands of sample thread.

Answers to some questions which you may be silently asking may be contained in the following data regarding the instrument shown in Figure 2. It has a clear aperture of 3½", with a focal length of 52½". The main tube dimensions are: Length 42", which includes ½" of No. 28 thread on each end—43½" length was ordered. Outside diameter 3¾", with a wall thickness of .128" (approximately ⅛"). This wall thickness is extra heavy and will probably stampede some of you. However, let it be said in defense of this heft of wall that the extra weight insures a very stable or rigid

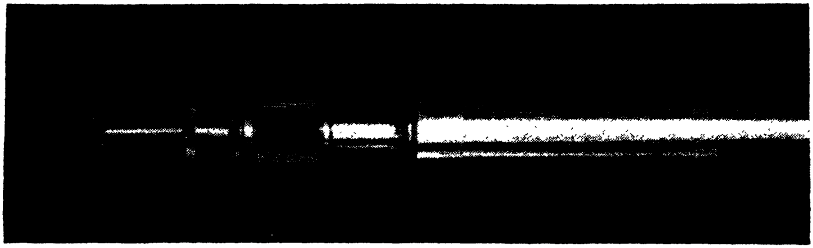


FIGURE 3

A close-up of the eye end of Figure 2, showing the micrometer focus control. The wide knurled band is the rotor, which is 2" in diameter. The two knurled rings to the left are stuffing box rings. The ample-sized rotor is easily seized with the bare or gloved fingers of either hand, from any position, thus making focusing both simple and convenient.

tube, one not easily damaged or thrown out of line by accidental knocks from different sources. An added cost of two or three dollars is little or nothing on a fine instrument. A heavy tube, when properly balanced, has a smooth and ponderous action, not easily affected by every little breeze that blows; also of notable importance, a ⅛" wall thickness permits reducing the diameter on each end of the tube sufficiently to form a good shoulder and cut a No. 28 thread for the control end assembly without weakening the tube. This assembly will weigh 6 to 8 pounds and will continually take the brunt of manipulation when in service. Amateurs' telescopes are generally—yes, generally—built too light; seldom if ever too heavy.

Machining the Main Tube: The plan of threading the main tube ½" back, to a shoulder on each end, has been adopted as offering the surest means of gaining and maintaining a mechanical axis with a high degree of truth. This plan also offers ease of assembly and dis-assembly, clean sightly design eliminating small screws, and requires about the same time and skill to produce as other methods.

Without further discussion on this point let us get down to business. Observe, please, the sequence of presentation, or what to do next, as it is important here and through the remainder of this chapter. If carefully followed you will be saved the embarrassment of doing your work over. In a screw cutting lathe, owned, borrowed, or rented, and of sufficient length to take the main tube between centers, chuck a billet of well seasoned hard wood (maple) about 12" to 14" in length, with sufficient stock to finish, when turned, to a diameter slightly larger than the inside diameter of the main tube. Support the loose end with the dead or tail center. With a wood turning gouge in the tool post of the lathe (do not try to turn by hand), machine the billet of wood to a diameter, say, 1/32" larger than the inside diameter of the main tube. Let us call this diameter "No. 1." Reduce this diameter 3 or 4 thousandths of an inch over most of the length, leaving 1" approximately of No. 1 diameter on each end. This reduced diameter is No. 2 diameter. Again reduce the diameter, as before, leaving 1" of No. 2 diameter on each end. Continue reducing the diameter, as above, until you are sure the diameter of the wood is smaller than the inside diameter of the tube. With a hand saw cut the wooden cylinder transversely into two equal lengths, which will give two tapered plugs. Do not remove the plug from the chuck, but move the tailstock back. Into one end of the main tube drop the loose plug. Over the plug in the chuck, assemble the other end of the main tube. Move up the tail center to its depression in the tail plug. In the drive end half inch (chuck end) of the main tube, drill the brass and bore the wooden plug for a 1/4" wood screw. Drive the screw, and with a hacksaw cut off the screw head close to the brass tube. The screw keeps the tube from turning on the plug. If the main tube is to be worked with a file and sandpaper (preferable for brass) to a finished surface, this is the time to do it.

The tail end of the brass tube is now machined forward 1" to a shoulder, reducing the diameter 1/16" or more. The chuck end of the tube is next machined back 1½", including the screw head, to a shoulder, reducing the diameter to correspond with the reduced diameter of the tail end.

A standard, No. 28 thread is cut on the reduced diameter of each end. With a parting tool set to leave ½" of the thread from the shoulder, cut rings from each end of the tube. Be sure to do the tail end first. The chuck end ring will include the screw. These rings of sample or key thread should be promptly witness-marked with the end from which each came.

While it is in the lathe, wrap the main tube smoothly with one or two thicknesses of firm wrapping paper, sticking down the edge and leaving the thread and shoulder on each end exposed. This covering protects the tube until the refractor is finished. Remove all from the lathe. Prickpunch the end of the screw and drill it out to free the ring on the chuck end plug. Even if the main tube, when mounted in the lathe, should look and revolve at the start like a glorified frankfurter—to exaggerate—it will make no difference. The machining and threading of each end, as described above,

will make the two ends concentric and parallel, with a common mechanical axis.

The Cell: The cell assembly for an objective is important; it should be carefully made. There is a wide variety in cell design (See "A.T.M.," also Bell, "The Telescope"). Sectional drawings and description of only two forms of cell will be included in this chapter.

The cell assembly is wisely made in two sections, one section being the

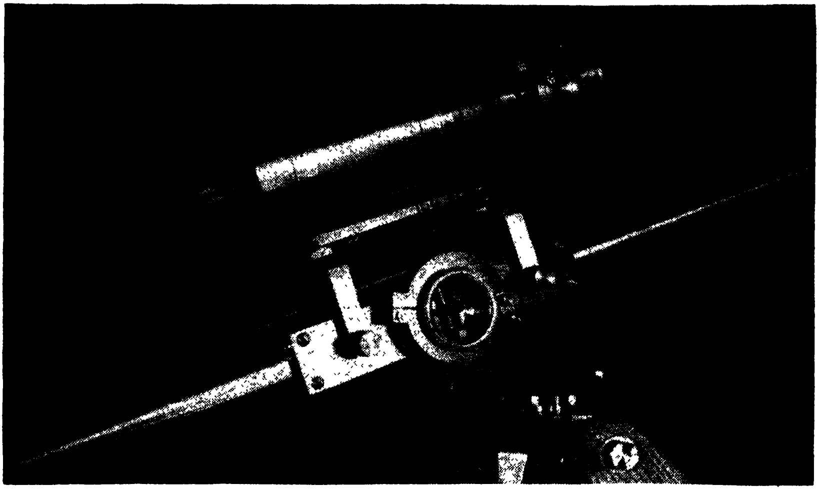


FIGURE 4

Another close-up of a part of Figure 2, showing the refractor mounting, also the short-focus reflector. While this reflector may be used as a finder, it was not mounted on the refractor primarily for that purpose but mainly because the same mounting serves both telescopes [It comes pretty close to being a richest-field telescope—see chapter on that subject.—Ed.]. The azimuth bearing is a 6° tapered cone 2½" long. Goosenecks support 2½" diameter hubs which are the bearings in altitude. These hubs are integral with heavy side plates, which in turn are fastened to a heavy supporting sleeve. The main tube slides through this close-fitting sleeve to the required balance, and is held from drifting by means of light pressure from the two thumbscrews on 1" curved, cork-faced, brass disks.

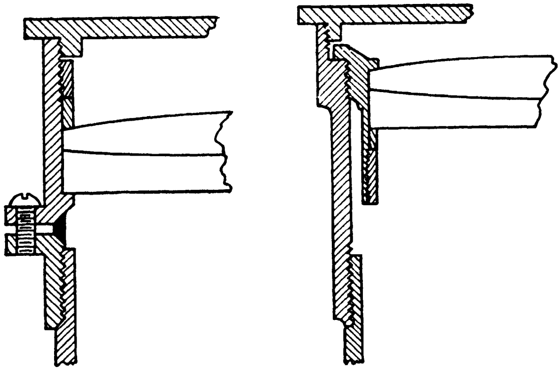
The mirror end of the reflector, with the mirror holding assembly, screws on the main tube. For a view of the inside, see Figure 8. The diagonal support is integral with the adapter tube, the whole assembling from inside the main tube into a chuck which holds this assembly firmly in adjustment. The clamping ring of the chuck can be seen just beyond the face of the eyepiece. The threaded shaft with thumbscrew heads on each end, moves the whole eyepiece assembly, including the diagonal, longitudinally in and out of focus.

The reflector mounting has a semi-universal joint in front, with a push-pull system at the mirror end, for adjusting and locking. By loosing four thumbscrews, the reflector with complete mounting can be taken off the refractor, and as easily replaced, without disturbing any adjustments previously made.

The device in the hub of the bearing in altitude regulates an internal expanding brake.

All bright surfaces, with the exception of the refractor main tube, are finished in baked-on lacquer.

outer cell, which screws to the main tube, the other section or inner cell, which holds the objective and screws into the outer cell. See Figure 5, left and right. The two forms here presented are a departure from standard design. The first form or design is adjustable and is machined from one casting. This requires making a pattern. The second form or design is not adjustable, and is made from heavy-wall brass tubing, thus eliminating the necessity of making a pattern and a casting. Some professional makers prefer adjustable cells, especially for objectives of 3″ and over. Other



All drawings by the author

FIGURE 5

The left-hand drawing is an adjustable outer cell, with three pull screws 120° apart, thus giving limited adjustment by rolling the halves of the cell on the double end cone. In this design the crown and flint of the objective are mounted direct in the object end half of the outer cell. The inner cell construction shown at the right is also suitable and desirable to use in the other design. By adding three push screws to the three pull screws the cell can be made straight push-pull in operation, thus making the double end cone unnecessary. The double end cone construction, with three pull screws, is the better design, chiefly because, with the double end cone, the joint is made practically dust proof, thus cutting down on the amount of cleaning necessary to keep the objective in good condition.

The right-hand drawing shows an inner cell construction in a non-adjustable outer cell casting. Any combination of the two drawings may be made to suit the user's requirements.

It will add to the appearance of the finished job if the rim of the protecting cap is knurled, also the edge of the sleeve of the inner cell and the object end edge of the inner cell.

expert makers will tell you that all work of centering—*i.e.*, coordinating the optical axis of the objective with the mechanical axis of the tube—should be so perfectly done as to make an adjustable cell unnecessary. If cell adjustments are necessary when your refractor is completed, it will be highly gratifying if the cell is adjustable.

The right hand sectional drawing shows how the cell is designed when an inner cell is to be used; the other shows how the objective can be successfully mounted in the end half of the adjustable or outer cell, thereby

eliminating the making of an inner cell. While this latter plan shortens the work, and would prove satisfactory in service, it lacks the convenience—easy and safe removal of the objective for cleaning, etc.— protection, and completeness of the first plan, which calls for an inner cell.

Here follow some practical details for making the complete adjustable cell assembly shown in both drawings. For clarity, the terms outer and inner cell will be used exclusively. The inner cell should be made first, in case the inner cell type, at the right, is chosen.

In the lathe, chuck a piece of brass tubing of sufficient diameter, wall thickness, and length. (Length includes desired length of inner cell, length of threaded sleeve, backing band, length of tubing held in jaws of chuck, plus, say, ¾″ for facing and four cut-offs). Use your own design for the inner cell, or follow the design shown. First, face the end of the tube. Increase the inside diameter of the tube to the actual or planned diameter of the objective (the objective may be made to the cell, or the reverse) to form one side of a collar or flange. This collar provides the front seat for the objective. Cut a thread on the inside of this new diameter, for the sleeve. Reduce the outside diameter of the tubing, as indicated in the drawing, in order to form the skirt of the inner cell. Cut the outside thread on the inner cell to the seat previously machined; this thread, of course, screws into the outer cell. With a parting tool cut off the cell thus far constructed, according to your requirements for length. Lay this cut off portion aside until the sleeve and backing band have been made from stock which remains in the chuck.

The sleeve should be made first. Reface the tubing at the cut-off and knurl the edge of the end before reducing the diameter and threading. The machining of the band is obvious. The fit of the band in the cell should be the same as for the objective, *i.e.,* so that it will just drop in without forcing—loose but not "sloppy."

After removing the tubing from the chuck, chuck a piece of cast iron or brass. This is to be machined and threaded as a mandrel on which the inner thread of the inner cell will screw. Screw the inner cell on the mandrel and finish the front or objective end of the inner cell.

The Outer Cell: It is assumed that the casting for the outer cell is now on hand, having been made from a pattern, as shown in Figures 2, 5, 6 at No. 1, and 8 at No. 2. The one-piece casting for a two-piece outer cell is firmly chucked and the rough surfaces "hogged" to approximate dimensions. Bore to requirement the inside diameter of the casting and cut the thread for the outside thread of the inner cell. Next, increase the inside diameter on the outside end of the casting, forward as required (see drawing) to a seat, for the seat on the outside diameter of the inner cell. This new inside diameter on the casting should be ⅛″ larger than the largest outside diameter of the inner cell. The seat should be deep enough, or far enough from the end, to permit the inner cell to be buried and leave at least ¼″ on the inside end of the casting, on which to cut a thread for a protecting cap or

cover. Machine the outside of the casting to the required dimensions and finish it.

Drilling holes in the flange of the casting for the adjusting screws is wisely the next step. Do this drilling on the drill press, removing from the lathe the chuck holding the casting. On the finished front face of the flange prickpunch the location of the drilling centers for the adjusting screws.

At this point you can choose between the outer cell design shown in Figure 5, and a push-pull design. The push-pull will require 6 screws, located in pairs—one push, one pull—around the flange, 120° apart, and will not require the separating band with cone end bearings (Figure 5, at left).

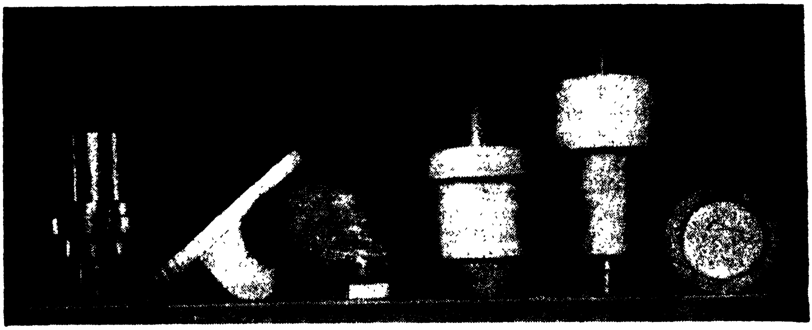


FIGURE 6

The various patterns used in making the refractor shown in Figure 1. From left to right. No. 1, adjustable cell. This pattern separates between the upper and middle ring for molding. The cylinder above the top ring is a core. The bottom cylinder is a core and is solid, for holding in the lathe chuck. Nos. 2 and 3 are for the mounting. No. 4 is a non-adjustable cell with core print on top and solid cylinder at bottom, for holding in the chuck. No. 5 is for the control end assembly. The core should run through the casting. No. 6 is a disk for the protecting cap.

If the adjustable cell design is adopted, only three pull screws need be used. They should be located 120° apart on the face of the flange. No. 8 round-head brass screws are a good size to use. Remember to witness-mark the flange of each half of the outer cell; also that the tapped holes for the push screws should go through the front half but not into the second half of the cell; that, after threading the holes for the pull screws in the casting, the latter is divided into two parts; and that the pull holes with a thread, in the front half of the cell, should be enlarged in order to allow the screw to slip through the hole.

Replace the chuck, with the casting, in the lathe. With a parting tool divide the casting into two parts, by cutting transversely through the flange from the circumference toward the center, leaving ⅛" of flange thickness or length for each part. Face the half of the casting which remains in the chuck, and bore and thread it to take the thread on the No. 1 end of the

main tube, using the No. 1 ring cut from the No. 1 end of the main tube as a sample or trial thread. Machine the outside end of inside diameter with a 45° taper, as per Figure 5, at left. Cut off from stock in chuck.

From a suitable piece of stock put in the chuck, a mandrel is made, on which to screw the front end of the front half of the cell. After the front half of the cell is mounted on the mandrel, face the flange and cut the 45° taper for the double-end cone. Machining the short band or double end cone with 45° taper on each end, from a piece of brass tubing, completes the outer cell.

Cell Assembly Made from Heavy-wall Tubing: The procedure in making a double cell (double: meaning outer and inner cell—although in this example the inner cell is not completely buried or encased in the outer cell) is practically the same as for the adjustable cell already described, except that there are no patterns to make, no castings to get, no flanges to divide, no adjusting screws to locate.

After the inner cell is complete and cut loose from the tubing in the chuck, as described above, and the threaded sleeve and backing band or ring made, it will become obvious that the tubing in the chuck is to be threaded to take the inner cell. When this thread is complete, screw the inner cell into place and finish the field end, and machine the outside surface of both cells. At the joint of the two cells it will be desirable to cut a shallow V, as a finishing touch, also to indicate the line of separation. To cut the thread on the outer cell which screws on the main tube, the outer cell is mounted on the mandrel described under "adjustable cell."

The objective, when not in use, should have some form of protective cap or cover. A brass disk with a knurled edge, which screws into the field end of the cell, is most complete and impressive and therefore the most desirable. To make this cap is not in any sense a problem, except in securely holding the stock in the lathe for machining. Here is a way to use the chuck for holding, which will probably prove successful if you do not attempt to take heavy cuts—in other words, if you will nurse the work along. Chuck a 1½" iron pipe coupling, face the end and remove it from the chuck. Chuck a disk of brass of suitable size, either cast or heavy plate, face an area of a size more than equal to the end of the pipe and remove it from the lathe. Solder the faced end of the pipe to the machined surface of the disk, centering them as best you can. Return the iron coupling to the chuck and machine a collar of suitable diameter on the brass disk. This collar should be not more than ¼" long, with a wall thickness of ⅛". On the outside of this collar cut a thread which will screw into the thread in the field end of the outer cell. Knurl the rim of the brass disk. Machine the chuck side or face of the brass disk, leaving the knurled rim ⅛" long or thick (however you view it) and cut the disk from the coupling. Support the disk in the chuck by expanding the jaws of the chuck against the inside wall of the collar. Daub a little pitch paste (pitch cut in acetone) on the jaws of the chuck, in order to keep the disk from slipping. Face what becomes the outside surface of the disk or cap, to a nice finish.

The Control End: On one end of the main tube is the cell with the objective. The other end of the main tube supports what will be called, for want of a better name, the control end assembly. This assembly, as produced by different makers, varies in the number of parts. The assembly here recommended, shown in Figures 1 and 7, consists of two tubes, the draw and focusing tubes, which telescope. These in turn slide as a unit in a bearing 3" or 4" in length of the tube, which is part of the casting. The end casting which carries these telescoping tubes with stuffing boxes, screws to the main tube.

To construct this assembly, proceed as follows. Buy a 15" length of brass tube having 1¼" inside diameter and a wall thickness of .030", also a 15" length of tube which will smoothly telescope over this piece, and with the same wall thickness. These 15" lengths will probably be longer than necessary and can be shortened to meet your requirement.

Make the pattern for the control end casting, after the designs in Figure 7 and No. 5 in Figure 6. The solid surplus end of the casting should be firmly chucked. Face the free or tail end, bore the bearing tube for the outside diameter of the focusing tube, also machine the channel between the bearing tube and the outer wall of the casting. Cut the internal thread on the casting for No. 2 end of the main tube, using No. 2 ring cut from the No. 2 end of the main tube, as a trial thread. Support the free end of the casting with the revolving tail center. Machine the outside surface of the casting to the required finish. Thread either end of the bearing tube for a stuffing box ring (36 to 40 threads per inch). With a parting tool, cut the end casting from the surplus piece in the chuck. From the surplus piece remaining in the chuck, or from other suitable stock, make four stuffing box rings, as per Figure 7 (two for the bearing tube ends and two for the focusing tube ends).

The Focus Control: A good focus depends on precise mechanism for focus control. The rack and pinion, in some form, continues to be standard on refractors, after decades if not centuries. You will profit in information and gain ideas if, before you decide on a focus control, you look over instruments such as the refractor, the transit, the microscope, also catalogues of the leading manufacturers of these instruments. The focus control to be here described is shown photographically in Figure 1, also in the drawing, Figure 7. This new adaptation of rack and pinion is recommended for the following reasons: its ease of assembly and disassembly, smooth action, sturdiness, good looks, and the important adjustable feature. (When a pinion shaft is supported in a box or bearing, it is a fussy job to get the pinion and rack in close and smooth adjustment; and when once attained, this adjustment should not be changed unless necessary.) With the new design it will be noted that the pinion shaft is eccentric in the cylinder which holds it. By turning this cylinder, when in place, the eccentric pinion is carried to any desired adjustment with the rack, and locked in place with a blind set screw. The time required to make this new design should be about the same as required to make any standard rack and pinion control for a

refractor. It may not be an exaggeration to add that the new design simplifies making a rack and pinion control, while offering a superior device.

Let us start a practical consideration of this new control by giving each major part a name, with a rough picture of how the parts assemble. See Figure 7.

The shield is fastened to the main tube by means of four screws with nuts.

The barrel extends through a hole in the shield, and is fastened to the shield, preferably by "sweating."

The sleeve which carries the half-moon-shaped piece which supports the rack, slides into the barrel, and is locked in place with a set screw in the wall of the barrel.

The cylinder carries the eccentric pinion shaft, pinion, and finger wheel, and slides into the sleeve, being locked in place with a set screw in the wall

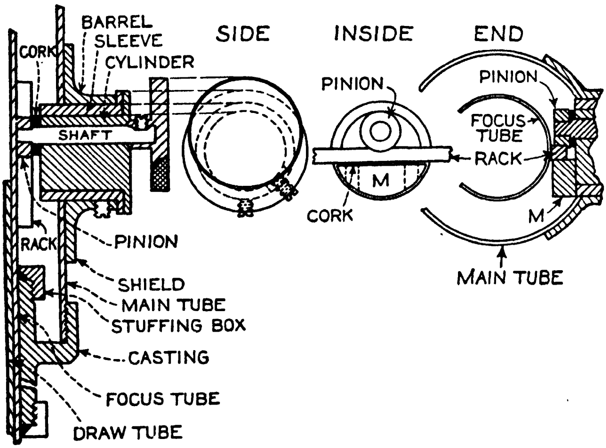


FIGURE 7
Details of the focus control.

of the barrel. This screw passes through an enlarged hole (for adjusting the sleeve with the rack) in the sleeve to bite on the cylinder.

A 2" length of rack is fastened to the focusing tube (not the draw tube, which slides through the focusing tube) preferably with a neat job in "sweating."

Brass rod, round stock of suitable diameter—1¼" or more—should be used from which to make the barrel, sleeve, cylinder, and finger wheel.

Study the sectional drawing in Figure 7 until you have a clear mental picture of just what to do, and how to proceed. Make additional drawings, with dimensions.

First, machine the barrel. Bore and machine the sleeve (note the flange on the sleeve, the rim of which should be knurled). Machine the outside

diameter of the sleeve from right to left, up to the flange. Fit the sleeve to the barrel by trying the barrel on the sleeve.

The cylinder is machined in the same manner as the sleeve, except for boring. The flange on the cylinder should be the same size as the flange on the sleeve, and the rim should be knurled. Fit the cylinder to the sleeve by trying the sleeve on the cylinder. Later, when the chuck is free (nothing in it), carefully chuck the cylinder and finish what becomes its outside face or end. Drilling the eccentric hole in the cylinder is preferably done in the lathe, by chucking the cylinder in the four-jaw independent chuck.

Machine the finger wheel to any desired design, and knurl the rim.

To locate the rack on the tube for sweating, scratch a line on the tube, squaring it with the end of the tube (use a try square), or put the tube in the lathe and scratch a line on it with a pointed tool in the tool post, by sliding the compound slide rest from right to left. Carefully clamp the section of rack to the tube at this scratched line, and "sweat," first tinning the surfaces.

(Note: Supporting tubes or tubing in a lathe may be greatly simplified by using a revolving cone tail center. The cone should have the standard 60° taper, and be at least 3" in diameter at the base of the cone. This size gives a wide range in usefulness. Such a revolving tail center is an important lathe accessory and should be made ball-bearing.)

We will again take up the sleeve, in order to complete it. The sleeve carries a half-moon-shaped section of a brass disk (see *M*, Figure 7) on which the rack rides, made as follows. Machine a brass disk to the outside diameter of the sleeve (slightly smaller), with a width or length equal to the width of the rack, plus 1/32". Machine a shoulder on the disk, letting the disk fit into the sleeve 1/32" (the two pieces will later be joined at this shoulder by "sweating"). With a hacksaw cut the desired section from the disk, finishing this cut on the section, in the lathe, by facing in a two-jaw chuck. On this finished face, 5/16" each side of center, (length) prick-punch for two 3/16" holes. Drill and tap them. Turn two small corks (bottle stoppers) into cylinders which will screw into the 3/16" holes. To cut the revolving cork use sandpaper. Fasten a small cork bottle stopper to a piece of 1/4" round brass rod, with hot pitch or sealing wax, and put the brass rod with the cork attached into the lathe chuck for turning down the cork. "Sweat" the half-moon-shaped segment or section to the sleeve. Screw the cork cylinders into the holes and, with a razor blade, cut off the corks to within 1/32" of the face of the segment, according to your requirement—in other words, so that the rack will ride flat and square on the corks.

The shield, when finished and mounted, should be about 2" square—curved, of course, to fit the main tube. Make it of annealed sheet brass 1/16" thick, accurately formed to the main tube, or from a section of brass tube of suitable dimensions. This should be machined on the inside for fit with the main tube, and finished on the outside to harmonize with the remainder of the job. This latter method is a definite procedure and takes, probably, no more time to make than bending sheet brass into a close fitting shield, though

it insures a superior result. Support the shield in the two-jaw chuck, in order to bore the hole for a snug fit with the barrel. Prickpunch the four corners of the shield for drilling for No. 6 oval-head brass screws. (Make your oval-head screws by turning a flat-head into an oval-head, by revolving chucked screw in lathe and filing flat head to oval shape.) Locate the shield on the main tube and clamp. Drill one hole and put in the screw with nut, turning the screw up snug. Repeat drilling holes and putting in screws, one at a time until the four are located.

The shield is now firmly fastened in place. With a scratch awl, mark the margin of the hole for the barrel in the shield, on the main tube. Re-

FIGURE 8

From left to right: No. 1 is a non-adjustable cell. No. 2 is a push-pull cell. No. 3 is a Porro prism box (inverting system housing). No. 4 is the template used in making No. 3. No. 5 is the mirror end assembly of the reflector shown in Figures 2 and 4. No. 6 is the adapter tube and diagonal support of the reflector shown in Figure 4.

move the shield from the main tube. Prickpunch around a line scratched on the main tube, on the line, a little more than 1/8″ apart. With an 1/8″ drill, drill the punch marks, taking out the circular piece. Finish the rough margins of the hole with a file. With the set screws in the barrel, facing down, fit the barrel into the hole of the shield and "sweat" the joint in a bunsen flame. Small bits of solder should be located at the joint on the back of the shield. If the outside surface of the shield and barrel are to be lacquered, this should be done as the next step, before the shield-barrel combination is fastened to the main tube "for keeps."

The pinion—a steel pinion is preferable with a brass rack—is sweated to the steel shaft. See Figure 7 and note the cone bearing of the finger wheel

in the cylinder, also note the cork washer $\frac{1}{16}''$ thick between the pinion and cylinder. When assembling the pinion shaft with the pinion, in the cylinder, compress the cork washer against the cylinder, with the thumb on the pinion. This compression is maintained by locking the finger wheel to the shaft by means of the set screw in the hub of the wheel. The cork washer gives smooth operating friction.

Stuffing boxes or some other equally effective form of adjustable friction, for the telescoping tubes, are highly desirable if not absolutely necessary. Good fitting tubes may for a time, when new, stay in place without much slipping. A tiny bit of wear, however, starts the slipping, and a slipping tube is a nuisance which can bring to the surface a lot of "cussing." So, at this time, make your stuffing boxes, four in number—one on each end of the casting bearing, and one on each end of the focusing tube. You will not regret the extra time, when you see how much these add to the general good looks and efficiency of your refractor. In addition to these desirable features, stuffing boxes have a tendency to keep the tubes centered, keep the tube polished, and act as a dust trap to the main tube. Detailed directions for making them are not necessary—Figure 7 tells the whole story. Knurl the outside rim of the ring. A strip of felt is used in the channel of the ring (More will be said about this strip of felt, under assembling). For stuffing boxes, 36 to 40 threads per inch will be found right.

Finish: In the matter of finish for your refractor you have at least two sound considerations from which to choose. One is to leave the brass bright, *i.e.,* polished. Beautifully made instruments, with polished brass surfaces, are invariably arrestingly impressive, even to the individual who acknowledges that he knows nothing about mechanical things. The same is also quite true of the second choice, which is to color the brass with an oxidizing agent. Butter of Antimony, applied with a brush or cloth pad, will change polished brass to a dark tobacco brown color. To maintain either the polished or colored surface without regular attention, the outside surface of the brass should be lacquered. Lacquering is a minor art in itself. With care the amateur, however, can do a successful and serviceable job.

Lacquer which is baked on, (Bakelite Corporation) should be used. With a fine, soft brush, apply a thin coat to the clean surface, let the pieces stand in a tin pan, to dry for a half hour, and then place the pan with its contents in the kitchen oven and bake at 270° F. for 20 minutes, or 200° for one hour. The latter temperature and time are safer for the amateur to use. Long pieces, such as a main tube, too long for the kitchen oven, should be taken to a professional finisher for lacquering. The draw and focusing tubes should not be lacquered.

Assembling the Parts: With the exception of the control end assembly, assembling the parts will offer no problem. If previous directions have been followed, the parts for the control end assembly are now ready to assemble. Proceed as follows: Screw the correct stuffing box ring, without felt, into place on the objective end of the tube bearing in the end casting. Slide the draw tube into the focusing tube. Enter the eye end of the focusing

tube (holding the draw tube) into the objective end of the bearing in the casting, and slide it through. From a piece of felt 1/16" or slightly greater in thickness, using a razor blade and straightedge, cut a strip 1/16" to 1/8" wide, according to requirement, long enough to wrap around the tube, butting the ends. After backing off (unscrewing) the stuffing box ring, tuck the strip of felt between the ring and tube, down into the channel in the ring. Screwing the ring back into place will compress the felt against the tube, giving any desired degree of friction. Deal with the three remaining stuffing box rings as above.

Next, screw the end casting to the main tube. Slide the sleeve into the barrel. Turn the focusing tube clockwise until the rack seats squarely on the two corks in the section on the sleeve. Lock the sleeve with the set screw. The cylinder complete, *i.e.*, with pinion, cork washer, pinion shaft, and finger wheel assembled, is now slid into the sleeve, the eccentric pinion brought into proper adjustment with the rack by turning the cylinder, after which the cylinder is locked with its set screw. A small amount of non-running lubricant can be used on the rack and pinion. Make small soft copper disks on which the set screws can bite, thus avoiding the scoring of the nicely machined surfaces.

Diaphragms: For a century or more the importance of diaphragms in a well blackened main tube has been stressed—stressed to such an extent that a refractor cannot be considered complete without a full complement of diaphragms. The number required will vary with the length of the refractor. If they are spaced 10" apart through the main tube, up to the field end of the draw tube, this will completely fulfill the requirements. (Exposed surfaces should be flat blackened.) One way to make a successful diaphragm is to expand a strip of 16-ounce copper or brass 1" wide, inside the main tube, with a 1/4" overlap. Scratch the overlap, remove and solder. This band is soldered inside the band, to a flat piece of 16-ounce copper or brass in which a suitable sized hole has been made. After the band is soldered to the flat piece, the surplus of flat piece around the band can be trimmed with snips and filed flush with the band. The varying size of hole requirement for each diaphragm can be taken from the lines of the elongated cone, representing the cone of light made by the objective, which should be a part of your lay-out drawing.

To place the diaphragms in the main tube, with a 1½" eyepiece from which the lenses have been removed, in the draw tube, slide the diaphragm with smallest hole, through the main tube, toward the control end, until you can see by looking through the lensless eyepiece, the smallest inside margin of the cell which is to hold the objective glass, yet can see no part of the inside wall of the main tube. Follow this practice in locating the remaining successive sizes.

The mounting: The term mounting, as used here, will mean the part or parts which are assembled between the head of the tripod and the main tube of the refractor. The alt-azimuth and the equatorial are two kinds of mountings. Figures 1 and 9 show an alt-azimuth mounting which is simple

in plan, suitable for small refractors and the ordinary requirements of the amateur.

Make working drawings. Make wooden patterns (¼″ to the foot oversize, to allow for contraction and finish of metal) for castings. (See Figure 6, Nos. 2 and 3.) Finish the contact or friction surfaces in the lathe. Finish the remainder of the castings by surface grinding or with a file. Machine the cone stud, giving it a 6° taper. Cut a thread on the small end for a ½″ nut. Chuck (two jaw) the tripod half of the mounting, and bore and

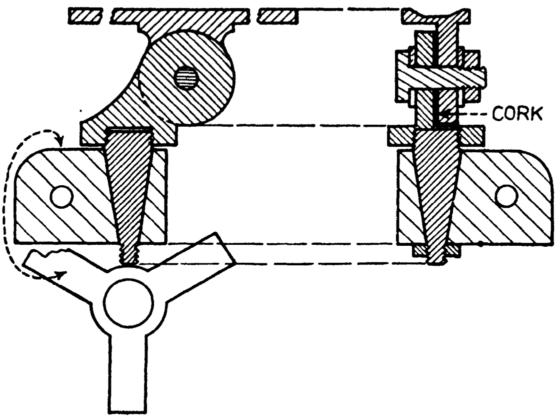


FIGURE 9

Details of an alt-azimuth mounting—the one shown in Figure 1.

thread for the cone stud. After drilling, the two castings are assembled with a ½″ brass bolt, with a spring lock washer under the nut.

The secret of the smooth holding friction in this joint lies in the cork washer between the surfaces. Use cork gasket material, 1/16″ or less thick. This may easily be found in hardware stores.

To machine the cone stud, you have set the lathe compound to 6°. Do not change this setting until after the tapered hole in the tripod head casting has been machined. Obviously, this tapered hole is to receive the tapered stud in order to make a tapered bearing. After the hole is machined for the stud, grind the stud into the hole, in order to get a velvet bearing, using optical emery and oil. In service the stud can be lubricated by rubbing it lightly with yellow laundry soap or with cup grease.

The bands which hold the main tube to the saddle casting should be made of annealed brass 1/16″ thick. The width of the band should be equal to the diameter of the objective. To measure the required length, wrap a strip of firm paper over the main tube, creasing the paper with the thumb nail along the joint of the tube and casting. Scratch flat brass stock from the paper measurement, and bend it in the vise. The use of bands for fasten-

ing the main tube to the saddle is superior to fastening the tube with screws to the saddle, as the bands permit of sliding the tube in either direction through the bands, to a required balance which can be changed when necessary. Again, bands are not likely to distort the shape of the tube, while fastening with screws might do so.

If an alt-azimuth mounting as above described is to be used, it should have enough frictional area and pressure easily to carry the load of the main tube in any position of altitude. A rough rule which should be safe to follow is: the diameter of the friction faces should be equal to the full diameter of the objective. (Friction depends in large measure on pressure, not area.) Thus, 2½" friction faces for a 2½" objective, 4" friction faces for a 4" objective (on the basis of $f/15$, which automatically gives tubes of relative length). A saddle casting having a length of three times the diameter of the objective, will give ample support to the main tube.

The Tripod: Aside from the common feature of three legs, (which all tripods seem to enjoy) there is considerable if not wide variation in tripod design. The material used is generally wood, brass or steel tubing.

Although the tripod properly comes under the general head of mounting, let us think of the assembly which supports the main tube and in turn is supported by the tripod, as the mounting. If the mounting which you have adopted makes special requirements of the tripod in the matter of assembly, then you should design your tripod to meet these requirements, also to meet any individual fancy in shape of legs. In any case, build for solidity. Dimensions and other detail of the tripod shown in Figure 1, which in service has proved highly satisfactory, are: weight 26 lbs., over-all length 6'. Each leg is made of two pieces of oak (white ash is equally good) 6' long, ¾" thick, 2½" wide at the top and 1½" wide at the bottom, spaced or separated with 1" sections of heavy brass pipe, through which pass 5/16" brass bolts. The head of the tripod is a casting in German silver (brass is suitable at two thirds the cost) with wings 1" in thickness, located 120° apart around a 2½" cylindrical center portion. See Figure 9. This three-winged casting should be machined to a smooth surface on top and bottom or two ends, and bored with a tapered hole, flat surfaces on the three wings. Surface grind them if you have the equipment, or use a file. The three wings and the tops of the legs, should be drilled for ½" brass bolts. Use heavy brass washers on either end of the bolt, with a spring lock washer under the nut. Drill the legs for the leg bolts, at 4", 12", 32" and 52" from the small end of the legs. To assemble, put the 5/16" brass bolts into the 4" and 12" holes, use washers, make up tight. Spring the leg halves apart, to drop in the separating pipe section at the 32" hole, and do the same at the 52" hole, leaving the top end to assemble last.

The foregoing detailed description will be easily followed and understood by the experienced craftsman. To the less experienced, or beginner who has a facile grasp of things mechanical, let it be said, it is not necessary that you should memorize the entire procedure in making a refractor, as here presented, or that you should carry the entire picture in your mind; a good

plan is to follow the sequence of presentation from the start, taking short sections to digest and then to make. This sequence thing is not a deep-dyed monster, but a friendly helper; it has been "checked and double checked" for your benefit.

For the convenience of the reader who desires information on where to purchase materials referred to in this chapter, the following firms with

Photo by The Hartford Times.

The author.

addresses are added. Undoubtedly other firms render equally good service to the customer. This is desirable information and in no sense intended to be an advertisement.

For brass tubing (bulletin listing sizes): Patterson Bros., 27 Park Row, New York, N. Y.

For rack and pinion parts (catalog): Boston Gear Works, Inc., North Quincy, Mass.

The Refracting Telescope—Principles of Operation and Construction

By J. R. HAVILAND
Member Technical Staff, Bell Telephone Laboratories Inc.

INTRODUCTION AND THEORETICAL CONSIDERATIONS

While it is true that a reflecting telescope can be made by the tyro—yes, even by the school boy, the production of a really fine mirror for it is a task to try the abilities and patience of a skillful, experienced worker. There can be no denying that a great deal of pleasure may be had from observing with a telescope whose perfection is far below that which is possible, and that the ultimate dissatisfaction with such an instrument frequently leads to another and usually more successful attempt. Be all this as it may, the production of a fine optical surface requires a great deal of skill. This may be acquired during the first attempt, but more frequently comes after several disks of glass have slid back and forth across laps on their way to more accurate figure.

The writer has been privileged to see and comment on many letters from the veritable avalanche which, during recent years, has descended upon the shoulders of A. G. Ingalls. These letters indicate that there are a large number of men (and a few women too) who have the mechanical equipment and tactile skill necessary for the production of an accurate optical surface.

The belief that the refracting telescope commends itself to amateur construction, and is more satisfactory for the amateur use than the reflector, furthered the thought that an article covering this type of telescope in detail, and written for those whose equipment consists of more than a barrel of rocks, would be welcome. It is far from the writer's intention to belittle any efforts, however meager, or to deny that beautiful reflecting telescopes have been produced by those whose skill transcended the need for any but the simplest tools. However, the optical and mechanical parts for a good refractor cannot be made on the kitchen table with a cold chisel and hammer, and a perusal of the photographs in "A.T.M." will indicate that many of the followers of this classic art did not make their instruments with the above-mentioned tools.

So, despite the satisfaction which may be obtained from crude telescopes made with a minimum expenditure of money and absence of tool equipment, the results from an instrument involving long, careful work and a not too great stricture of the purse will be gratifying.

What follows lays no great claim to originality. It sets down the results of the writer's experience and that of his more accomplished "brothers in combat." The methods of grinding and polishing glass to be described are those of the professional opticians of highest rank and, while these methods require mechanical equipment, most of this may be cheaply constructed in a moderately well-equipt home shop. When I say cheaply, I ignore time. For what is a hobby, if not to murder time—every moment of which is enjoyable. If the pleasure be not present the work is no longer a hobby but an arduous task. Considerable space has been devoted to what it is

hoped will be regarded as minute instructions covering the design and formation of a lens. An attempt has been made to explain, as simply as may be, the optical principles involved in the performance of an achromatic object glass.

While approximate methods of design are used, references are appended that will permit the enthusiast to wander off into the fields of correcting for coma, or producing objectives of wide angle, if his courage lead him this far. The type of objective described, however, will leave little to be desired if properly executed and *mounted.*

Particular attention is directed to the discussion of the degree of accuracy required in the production of a reflecting surface, as contrasted to that which is necessary in making a refractor. The conclusion regarding this much-argued question is that of A. A. Michelson, and is one of the more important reasons for the selection of a refracting telescope for our task.

The reflecting telescope has three sterling advantages—perfect achromatism, great aperture ratio, and cheapness. The perfect achromatism of the reflector is upset by ordinary eyepieces when used with mirrors of the usual $f/8$ ratio. Huygenian eyepieces perform unsatisfactorily as regards both spherical and color aberration for ratios much below $f/12$. The precision of figure necessary is very difficult to attain, especially by the Foucault test at center of curvature. The silver coat must frequently be renewed in most urban localities and re-collimation of the instrument after returning the mirror to its cell is a tiresome task. Wide aperture objectives are very sensitive to collimation and a slight misalinement is ruinous to the image.

The outstanding advantage of a reflector is, therefore, cheapness and for celestial photography. For the latter purpose an $f/5$ mirror is a valuable tool, but a mirror of such large relative aperture lies far beyond the capabilities of the average beginner.

The refractor suffers from three disadvantages. Optical glass suitable for a first class lens is expensive—three to ten times the cost of Pyrex or Tempax, depending on the diameter. The telescope runs to awkward lengths in the larger diameters, since a focal ratio of 15 is employed for those over 4″ aperture, and it will not be nearly as satisfactory for photography, where light concentration and achromatism count most heavily. Refractors may be designed for photographic use and corrected for the violet end of the spectrum. Properly designed as to curvature, they will embrace several square degrees, with good definition to the edge. The latter performance cannot be equalled even by the new Ritchey-Chrètien curves and other optical tricks which have recently been developed for reflectors.

It is possible to make a three-lens apochromat for photo-visual work in which the more actinic rays at the violet end of the spectrum come to the same focus as those in the visually brighter green-yellow portion. Such a combination permits observation and subsequent photography at the same focus. While the mechanical construction of a three-lens objective offers no particular difficulties, the computation for such a lens is involved. Special glasses whose ratio of dispersion to refractive index lies off the beaten path are required, and are very expensive in consequence. The design of such

an objective, interesting as it is, lies beyond the scope of this article, as a design by tedious trigonometric trace is one to give pause to those who are not mathematically inclined.

These are the things that recommend the refractor: it is easier to make—yes, easier to make—than a reflector. Perhaps this statement requires qualification. Naturally, the four surfaces involved in a refractor cannot be ground and polished in as short a time as the single one needed for a reflector. But the precision of figure required for any surface of a refractor is less than that which is necessary for a reflector. We will refer to this again and in a definite, quantitative manner. The matter, however, is one of paramount importance, since it permits the comparatively inexpert to make a telescope that will define instead of forming a star image like an ink splatter (as is, alas, too frequently the case with many reflectors). The surfaces of a refractor are spherical, and their steep curvatures tend to keep them so in grinding and polishing. Focal ratios of 15 further ease the accuracy requirements.

At this point it might not be amiss for us to examine into just what precision of focus is required for perfection of performance of refractor and reflector.

Airy, Rayleigh and others, in their investigation of image formation, arrived at the following conclusions regarding definition. All rays originating at a point in the object under observation must arrive at a point in the image (after refraction or reflection by the objective) by paths whose lengths should vary by not more than a quarter wave-length of light (5 millionths of an inch). Considering a mathematical point for an object—a condition, for all practical purposes fulfilled by a star—an image will be formed which is not a true image of the star but a pattern formed by the interference effects of light. This pattern consists of a central bright spot surrounded by so-called diffraction rings which are concentric, alternate light and dark bands, equally spaced radially.

Eighty-five percent of the light in the image is concentrated in the central spot and, for this reason, not more than two rings are of sufficient luminosity to be visible at focus. The diameter of the central dot is an inverse function of the diameter of the objective. Thus we have the paradoxical condition that, the larger the diameter of the telescope, the smaller the star image. However, due to an effect known as irradiation, which is a condition on the retina of the eye similar to halation effects in photography, a star observed by a large telescope may not look smaller than when seen through a smaller objective. In any event, the diameter of the central image formed by rays whose path difference does not exceed one-quarter lambda is given by the formula:

$$D = \frac{1.22\,\lambda f}{R}$$

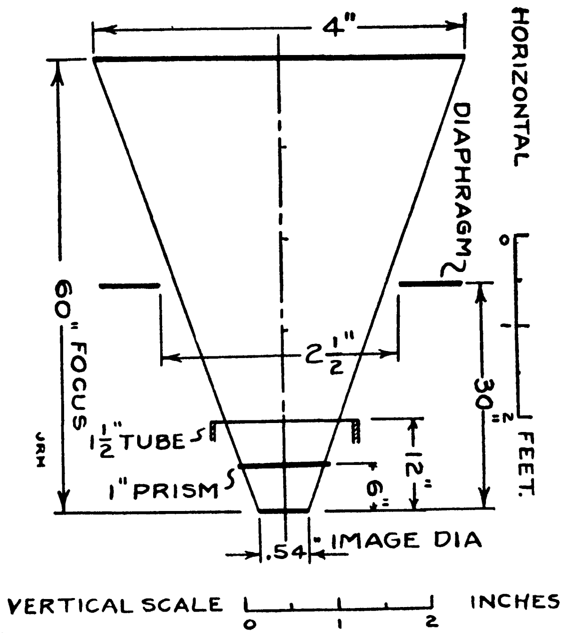
where f = focal length
R = radius of objective
λ = wave-length of light

This leads us to the matter of resolution and definition. For two stars to be visible as such, and not form a single image, the relation between their separation and the diameter of the objective must be:

$$\text{separation} = \frac{4.5 \textit{ seconds of arc}}{A}$$

where A is the diameter of the objective. Thus a 4½″ diameter telescope will just separate two stars whose separation on the celestial sphere is one second of arc.

It may be mentioned parenthetically that an image of a finite object subtends the same angle at the focus as the object. For example, the moon subtends an angle of approximately 30′. The size, therefore, of the image



All drawings and photographs by the author

FIGURE 1

of the moon is determined by the focal length of the telescope, and is independent of the diameter of the objective. The size of the image is important in reflectors when selecting a prism of proper size, and in refractors when determining the size of holes in diaphragms and eye tubes.

To take a concrete example, consider a 4″ telescope of 60″ focal length. The tangent of 30 minutes is approximately .009, so that .009 × 60″=.54″, the diameter of the image. If a scale layout of the system be drawn, with the lens diameter and image size full scale and the focal length 1⁄12 scale, and lines are drawn connecting the extremities of the lines representing the lens and image, as shown in Figure 1, the minimum diameter of diaphragms and

tubes may be graphically determined. An eyepiece tube, prism diagonal, and diaphragm are indicated on the figure.

Note that the minimum diameter is not selected, but that a generous clearance is allowed. Too small a diaphragm hole reduces the effective diameter of the objective—that is, the light coming from the outside zone is stopt off. The moon's angular diameter (which, by the way is approximately the same as the sun's) is selected, since 30′ is about the field visible with the telescope with the lowest powered eyepiece ordinarily used.

Aside from the advantage of better definition, an increase in the diameter of an objective has another and perhaps just as important advantage, namely, light grasp. Since the amount of light gathered by an objective is obviously proportional to its area, it follows that doubling the diameter multiplies the light grasp by 4. Unfortunately, increase in diameter augments the troubles arising from atmospheric disturbances which distort the image and deteriorate definition. Better seeing conditions (steadier atmosphere) are therefore required for the utilization of the full defining power of larger apertures. Bell strikes a happy medium of about 9″ for optimum satisfaction, weighing the advantage of increased light and resolving power against average seeing conditions. The amateur will not be concerned with 9″ refractors, because of the expense of making and mounting a 10′ telescope. Six inches is perhaps the upper limit, and 3″ to 5″ the more usual size. A 3″ glass will give beautiful views of the planets, moon and sun, and will have the additional advantage of portability. A 5″ will out-perform the usual 6″ reflector in brilliance of image and definition.

This brings us, after thus digressing, to what precision of surface is required. Let us, for the sake of comparison (which Shakespeare considered odious) consider first the reflector. We found that a path difference of rays from object to image must not exceed $\frac{1}{4}\ \lambda$ for practically perfect definition—that is, any improvement in the figure of the objective which will reduce path difference to a value below this amount will not noticeably improve the image. As a matter of fact, a path difference of twice this amount may be tolerated, and the deterioration of image resulting may be annulled by minute re-focusing. As the latter condition requires a surface sufficiently difficult to produce, we will consider this the allowable tolerance and proceed from this hypothesis.

For a reflecting surface to return light rays arriving parallel to the optical axis to a focus, its shape must be paraboloidal. From the mathematical properties of the paraboloid it may be discovered that the center of curvature of the small central zone falls on the optical axis at a point nearer to the curve than the center of curvature of the edge zone. This difference in distance is defined with sufficient accuracy by the relation:

$$D = \frac{r^2}{2\mathrm{R}}$$

where D is the separation between the points
r the radius of the edge zone
R the radius of curvature

Foucault's ingenious method of determining centers of curvature, by inserting a knife-edge in the cone of light returned from a pinhole situated at the average center of curvature of a mirror, has been described in such detail in "A.T.M." that nothing could here be added. The eye, however, is very poor in photometric estimation when the illumination of two separated areas is to be compared. Amateur repetitive placement of the knife-edge to within .010″ of a previous trial may be considered excellent in determining the center of curvature, and .015″ very good. J. H. King (and independently Kirkham and Wright) has modified the Ronchi test in such a manner that quantitative results in the determination of figure may be obtained with possibly greater precision than by Foucault's method. (See also p. 258, Martin, "Applied Optics," Vol. 2.) His method, however, is new and, while it appears excellent, has still to stand the test of use by other less skilled operatives. Of the brilliant invention by the same author, which permits testing convex surfaces with precision, no such doubt exists, and his method of disposing of this most serious bug-a-boo will be found elsewhere in this volume under his name.

Let us, however, determine just how close the knife-edge must be placed in the figuring of an $f/8$ mirror so that the path of rays, when the telescope is used on a celestial object, shall fall within the $\lambda/2$ limit.

Bell gives the following formula for parallel incident light:

$$df = dp \times 8\left(\frac{f}{A}\right)^2$$

where df=change in focus (axial distance)

dp=difference in path length

$\frac{f}{A}$=aperture figure of the telescope.

Assuming that $\frac{1}{2}\lambda = .00001''$, and a focal ratio of 8, we get, by substituting in the above formula:

$$df = .00001'' \times 8 \times 64 = .005'' \text{ approx.}$$

Now, since the pinhole stands still, doubling the motion of the knife-edge (our old formula r^2/R), and since the transition from light originating at the center of curvature to light originating at infinity halves the aberration, we have an allowable error in reading the knife-edge of $4 \times .005''$, or .020″, before exceeding our criterion of allowable error. It will be apparent that this is not beyond the realm of possibility and it, in fact, explains why it has been possible for so many amateurs to make mirrors that perform creditably. The accuracy required is a function of the focal ratio, and a substitution in the formula for a $f/5$ mirror will indicate that, for this focal ratio, the knife-edge must be placed within an error of less than .008″ for good performance. This is a rigid requirement and one that can be met by but few.

If it be borne in mind that the error allowed in the above discussion must be halved, in order to obtain a practically perfect mirror, the difficulty of testing at center of curvature is made clear. So difficult, indeed, is the

production of a perfect surface by this method that Prof. Ritchey, whose unsurpassed skill has figured the world's largest mirrors, is of the opinion that it cannot be done, except by the most expert.

We will now examine Michelson's equations from pages 71–72 in his "Studies in Optics," regarding the accuracy of surface required for an allowable path difference of rays leaving any two zones of an objective—say an edge and a central zone.

Recalling that with a perfect objective not all the light is concentrated in a single image, but makes a diffraction pattern consisting of a bright central spot surrounded by rings, we shall, nevertheless, for the purpose of comparison, consider the intensity of this central area to be unity. Then the following table lists the relative illumination of this spot for various path differences:

Total path variation (in wave-lengths)	Percent of light in central spot
0	100
¼	95
½	80
1	39

Thus, for a path difference of $\frac{1}{4}\lambda$ the light concentrated in this central spot will be 95 percent of that in the image formed by a theoretically perfect objective. With $\frac{1}{2}\lambda$ only 20 percent of the light possible is scattered—which is not too bad.

Michelson's formula for the allowable variation from truth of a surface for $\frac{1}{4}\lambda$ path difference follows:

$$\epsilon = \frac{-\lambda}{4(\cos i - \mu \cos r)}$$

where ϵ=variation of surface
i =angle of incidence
r =angle of refraction or reflection

For a reflecting surface, with entering light parallel and parallel to the axis, the angle i is very small and its cosine is, therefore, nearly unity. For example, $i = 2°$ for the edge ray from a 6″, $f/8$ mirror. Since the angles of incidence and reflection are equal, $r=i$. Substituting these values in the equation we have:

$$\epsilon = \frac{\lambda}{8} \qquad (\mu = -1 \text{ for reflection})$$

This tells us that, in a reflecting telescope, for an edge ray to meet a ray from the center so that their path difference shall be $\frac{1}{4}\lambda$, the surface may not depart from mathematical truth by more than $\frac{1}{8}\lambda$.

For a refracting surface our expression becomes:

$$\frac{\lambda}{4(\mu \cos r - \cos i)} = \frac{\lambda}{4(\mu \times 1 - 1)} = \frac{\lambda}{4(\mu - 1)}$$

where: μ is the average refractive index of the lens—say 1.5.

Substituting this value, we get

$$\epsilon = \frac{\lambda}{2}$$

Thus it appears that the surface of a reflector must be figured to an accuracy four times as great as a surface of a refractor. Added to this is the fact that a refractor is worked to an aperture ratio ($f/15$) half that of the usual reflector ($f/8$) and by virtue of this is, as previously noted, only one fourth as sensitive to inaccuracy of figure. Further, the refractor is figured at focus, so that the bug-bear of estimating shadows for zonal measurement vanishes. A perfect surface shows a uniform darkening of the entire aperture—no zones to measure, no shadows to judge.

Thus, while you will find the preliminary grinding and polishing of the four surfaces of a refractor more work than preparing the single surface of a reflector, how much easier from then on! Why not try one and see?

The writer recently had the privilege of observing the same object (Jupiter) with the 24″ Cassegrain and the 10″ refractor at the Franklin Institute at Philadelphia. The seeing was poor, which seriously handicapped the larger aperture but, even allowing for this, the performance of the refractor showed a marked superiority.

Having thus outlined what is at best the writer's opinion of the desirability of making a refracting telescope, and some of the theoretical and practical reasons supporting such contention, we will proceed to the notice of the properties of an achromatic lens.

If, by this time, the reader feels that he has become involved in a highly mathematical situation for which he has neither the talent nor inclination, he may be reassured that, should he fail to understand a single word of what has preceded, or the optical discussion which immediately follows, he can still make an excellent refractor by following the rather simple instructions under the heading, "Making an Achromatic Object Glass." In fact, the lenses of many of the world's greatest refractors were made by men who actually had no concern with the mathematics involved, but who possessed the necessary patience, and through practice acquired the skill needed for the perfection of this beautiful task—the generation of the most precise surfaces possible—surfaces to measure whose defects, the light wave—a fifty thousandth of an inch—must needs be split in eight parts!

The mathematical work necessary for the complete design of a simple achromatic lens is far from simple. Optical computation is perhaps not so difficult as it is cumbersome, but this need not concern the amateur unless his interest leads him in that direction. Great mathematicians have reduced the intricacies to such form that a good lens may be computed by any one who can substitute numbers from a table into a simple formula. So what immediately follows may be ignored by those who, perhaps with some reason, care nothing for the principles involved, but who do want to enjoy the possession of a good telescope—either for the pride which naturally follows

the accomplishment of such a worth-while work or for the moving observation of those majestic bodies which people the celestial sphere.

Since the terms refractive index, dispersion, and proportional dispersion bob up continually in the vernacular of optics, it may be of interest to get a grasp of what the terms mean.

The texts tell us that when a ray of light passes from a medium of one refractive index to one of another it suffers reflection and refraction. This sounds very complicated but in reality is very simple. For example: for-

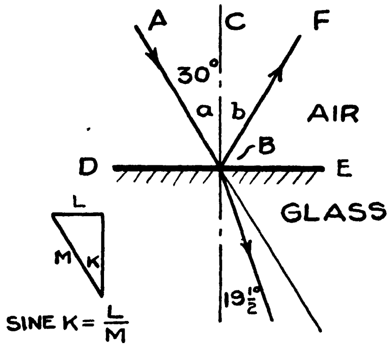


FIGURE 2

getting the term "refractive index" for the moment, let us suppose a ray of light *AB,* in air, strikes the surface of a plate of glass obliquely. Referring to Figure 2, *BC* is perpendicular to the surface *DE* and is termed the normal. Part of the light is reflected along *BF* in such manner that the angle *b* that the reflected ray makes with the normal is equal to angle *a* of the incident ray.

Put concisely, the law states that when a ray of light is reflected from a surface, the angles of incidence and reflection are equal. It will be noted that these angles are measured from the normal and not from the surface. As the angle of incidence increases, the pefcent of light reflected increases, being a minimum at perpendicular (normal) incidence (about 5 percent, air to glass) and increasing to 100 percent at some ("critical" is the name) angle which may be almost 90° or much less, depending on the media. We are not much interested in reflected light in our telescope for, valuable as this property is in the reflector, light reflected from the surfaces of our lenses is not only lost but in some instances, as we shall see, may seriously injure the image.

Returning to our diagram, if the angles are as shown in the figure, that portion of the light which is not reflected will enter the glass and, in so doing, will suffer a bending. In this case passing, as it does, from a rare to a dense medium, it will be bent toward the normal. The measure of bending is called refractive index and is the ratio of the sines of angles

made with the normal before and after bending. (In a right triangle the sine is the number obtained by dividing the side opposite an angle by the hypothenuse. Thus in a triangle having for its angles 30°, 60°, and 90° the sine of 30° is ½ or .5, since, in such a triangle, the hypothenuse is twice the short side.)

Let us assume that our ray makes an angle of 30° with the normal before, and an angle of 19.5° after, refraction. We find, from the tables which list the sines of angles, that the sine of 19.5° is .333, approximately. Dividing the sine of 30° by the sine of 19.5° (.5 ÷ .333) we get 1.5. The refractive index of the glass, therefore, is 1½ times the refractive index of air. Air

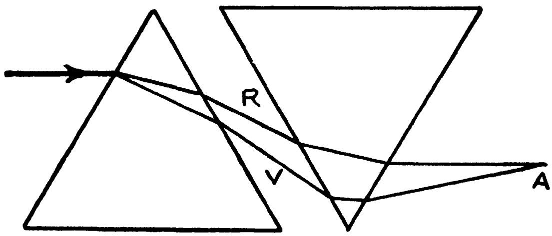


FIGURE 3

is arbitrarily taken to have a ref. index of 1, so it follows that our glass has an index of 1.5. In general, the denser the glass the higher the refractive index. The symbol μ (the Greek letter μ, pronounced "mew") is used to designate this quantity in the tables which list the properties of optical glass. If this letter has another letter as a subscript to it, thus μ_D, the subscript designates the spectral line for which the refractive index is given. D above, therefore, would mean the refractive index for D, the yellow line of sodium.

It happens that light of different colors suffers different refractions. The violet end of the spectrum is bent toward the normal more than the red. If, therefore, a glass prism be placed, as shown by the first prism in Figure 3, in the path of a ray of white light, the light will leave split up into its component colors in a rainbow strip, ranging from red which is refracted the least, to violet which, as noted above, is refracted the most. Such a strip is called a spectrum.

This spreading out into a spectrum is called dispersion, for reasons which are self-evident—the light being literally dispersed. Not all glasses have the same dispersive powers and fortunately, as we shall see, dispersion is not proportional to refractive index. This means that glass of a high index of refraction will not of necessity spread the spectrum into a proportionately wider band than a glass of lower index. This property is important and, at the risk of being tiresome, one word further will be added. A glass of high index will necessarily bend the light more than a glass of low index. The point is that the spread from red to violet may not be the same, propor-

tionately. Sir Isaac Newton, in his classical experiments along this line, drew the erroneous conclusion that dispersion and refractive index were proportional and, for reasons which will shortly appear, abandoned the consideration of the refracting telescope.

We are now ready for the consideration of dispersion as applied to the construction of our lens. Consider two prisms arranged as shown in Figure 3. If a beam of light is passed through the first prism it will be broken up into a spectrum in which the red (R) and violet (V) rays will be separated as shown. If a second prism be inserted as shown the violet ray entering this prism will be refracted more than the red and at the point A will meet it.

This is the principle of the achromatic lens. Referring to Figure 4*a*, the double convex lens by itself would separate a ray of white light entering

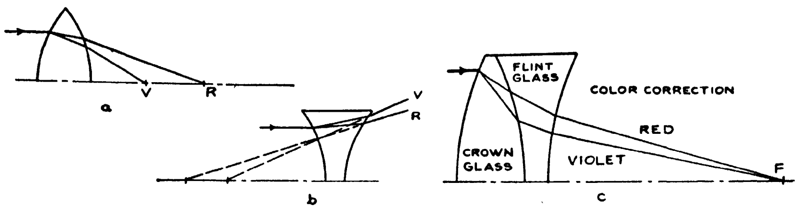


FIGURE 4

it into a spectrum, and the path of the red and violet rays would be as indicated by the lines. If, now, a concave lens be inserted in the beam, these red and violet rays will be refracted in the opposite direction Figure 4*b*, and if the curvature and optical properties of the second lens are of the correct magnitude the red and violet rays will be brought to a common focus (F), Figure 4*c*.

It follows from the above that the properties of two glasses suitable for the formation of an achromatic objective are, that the refractive indices shall be different and the partial dispersions throughout the spectrum for one glass be exactly proportional to those of the other. The refractive indices must differ since, were they the same, one lens would exactly annul the effects of the other and no convergence of light to a focus would result. Further, if the dispersions were exactly proportional, all the colors throughout the spectrum would be brought to the same focus and perfect achromatism would result. Unfortunately, no glasses are available which have this latter property, and those which approach it are very expensive and, because of other optical reasons, require very steep curvatures to make an objective of the usual ratio of focal length to diameter.

In the average combination with which we are concerned, partial achromatization is secured by bringing the C and F lines of the spectrum to a common focus. With good glass, all the colors between the red-orange and yellow-green will come very closely to this same focus and combine to

make white light. Due to the flint (concave) lens refracting the blue-violet more strongly, it will slightly overpower the first lens and these rays will therefore come to a focus back of the average focus for those between orange and green. Thus at the best focus the section of this violet cone of light will be a larger circle than the apex of the C—F cone, and will appear as a violet haze about the image. This sounds worse than it is, and with the average objective, even on extended bright objects of which the planet Venus is the most trying, it is unobtrusive. What has been said for the

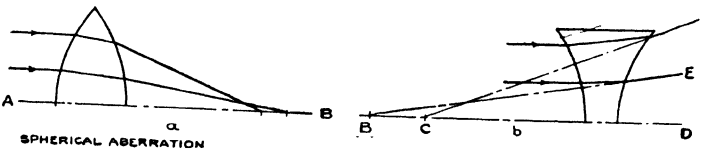


FIGURE 5

violet is true also for red, but this light is of such low visibility as to have practically no effect on the image.

Regarding the matter of focal ratios, we refer again to Bell. Assuming an aberration due to color, of the order of 1/2,000 of the focal length, he ties up the ratio between focus and aperture by the following equation:

$$f=2.8A^2 \text{ where } A=\text{dia. of aperture}$$

In this, Conrady differs somewhat, using 5 instead of 2.8. The former seems rather larger than need be. In any case an objective of approximately 5″ diameter would, by this formula, have an aperture ratio of 15. More exactly it would be 14, but the point of the matter is that objectives of smaller diameter can be worked to smaller focal ratios, while larger ones should have ratios in excess of 15. Thus a 3″ objective could be worked to $f/8$ and be expected to have a color correction equal to that of a 10″ with a focal ratio of $f/28$. It is this unfortunate situation that led to Prof. Conrady's opinion that very large refractors are impractical. Nevertheless an examination of the photographs taken with the very large refractors at American observatories would indicate, to the layman at least, that not much improvement could be desired.

Having disposed of correction for color, we will consider the correction of spherical aberration.

Consider a double convex lens with two rays of light incident to one of its surfaces, as shown in Figure 5*a*. It will be noticed that the ray passing through the lens near its edge crosses the optic axis AB of the lens at a point nearer the lens than the ray passing through the lens nearer the axis. Any converging lens, with spherical surfaces, suffers from this defect, which bears the tongue-twisting name of spherical aberration. With parallel light incident to the convex surface a plano-convex lens approaches very closely the smallest amount of this fault possible with a single lens. It will perhaps be apparent from the nature of the figure that, if the front surface of the

lens be given such a shape as to increase its radius of curvature as the edge is approached, this defect could be minimized.

Our paraboloidal mirror does just this—and the aberrations of a spherical mirror are cured in this manner. For a spherical mirror pitches the rays reflected from an edge zone inward too strongly and must be "corrected" (parabolized) for all zones, so that it may direct the light to the same focus. If the paraboloid be considered a corrected mirror, then a sphere is said to be under-corrected and an hyperbola over-corrected. Put another way, a mirror whose peripheral zone brings light to a focus inside the average focus is under-corrected, while one in which the light from the edge area over-shoots this point is over-corrected.

The same terms apply to lenses: under-corrected lenses are said to have a short edge, i.e., edge zone focuses short, while a long edge means over-correction. The effect of turned down edge on a lens is the reverse of that on a mirror. If the first surface of an objective (considered convex) has a turned down edge, the radius of curvature of the narrow zone thus turned down will be shorter than that of the rest of the surface. This will have the effect of bringing light traversing that zone to a shorter focus. Unfortunately a turned down edge on the back surface of the objective (considered concave or flat) has the effect of lengthening the radius of curvature of this edge zone. Thus the concave lens becomes "weaker" in this defective zone and does not pitch the light out sufficiently at the edge to balance the convergence of the convex component, and again the result is the same—the light focuses short. This explains why, in a reflector where a turned edge focuses long, it is the fuzzy image inside of focus which indicates a turned edge, and in the refractor the image outside of focus shows a blur when this obnoxious fault is present.

Consider now a double concave lens with parallel light incident to its front surface, Figure *5b*. The ray passing through the lens near its edge will be pitched out more strongly than the one near the center, and will take a direction as if it came from *C*. The more nearly central ray will be directed along the line *BE*. It will now be clear that if a convex lens, which pitches edge rays in too strongly, be combined with a concave lens which throws edge rays outward too much, the spherical aberration of the combination can be reduced to a very small amount.

The computation of the curvatures of two such lenses is an involved exercise in algebra and one which the average amateur will shun. As clear an exposition of the mathematics of this situation as has come to the writer's attention appears on page 33, Martin, "Applied Optics," Vol. II. The method of correcting an uncemented objective for coma which immediately follows is also recommended with confidence.

However, it is not necessary for us to concern ourselves too deeply with the involved process of designing our curves to annul spherical aberration. Certain forms of objectives reduce this quantity to a minimum. One of these is the one selected for our exercise: an equi-convex crown followed

by a plano-concave flint with its concave surface fitting the convex of the crown.

In the production of commercial objectives it is important that the surfaces of all lenses be spherical, since non-spherical surfaces cannot be produced automatically by machine. We amateurs care nothing about this, because our final job will be to remove spherical aberration by figuring, just as it is done in making a reflector. We shall not, however, have to guess when one shadow is the same as another. In our figuring, the knife-edge is placed at focus and when all aberrations have been annulled a uniform darkening of the illuminated objective will result. Who knows, then, whether the final figure on the back surface of our objective is spherical or not, or whether the curves we selected for our lenses were the best for the glass used—and, it may be remarked, who cares! If our objective shows a uniform gray when tested with the knife-edge, spherical aberration has been cured and this, after all, is the important item.

The question of coma deserves a word. Coma causes the light in the image to be unequally distributed, one side of the image receiving more than the other. A lens corrected for this defect will embrace a larger angle without distorting the image than one left uncorrected. Said another way, light arriving so that it is not parallel to the axis will still be brought to the proper focus. Since our field of view need embrace but a few minutes of arc, this is not a serious matter, but a lens suffering from coma must be accurately adjusted so that its optical axis and that of the eye-piece coincide as closely as may be. If this precaution be neglected a star image like "a," Figure 10, "A.T.M.," page 429, will result. Thus, if coma be present in an objective, great pains must be taken in squaring on. Realizing this, we still consider the cemented objective suitable for our task. As noted elsewhere, a cemented objective cannot, in general, be corrected for coma. What little is present in our objective can be reduced completely for the angular field required by careful adjustment (collimation) of the optical parts. In a refractor, once these adjustments are attended to, no re-adjustment should ever be necessary.

The various properties of glass mentioned above, with additional necessary data, are listed in the manufacturers' tables. An explanation of these tables follows later. However, most optical glass makers select certain limited glasses to recommend for our purpose and their selection may be relied upon.

Aside from the selection of glass for its refractive and dispersive powers, the quality of the glass itself is extremely important. Glass which is suitable for the exacting conditions imposed for telescopic usage must be precision annealed, free from large bubbles, of high transparency and free from striæ. Imperfect annealing is a very serious defect and has two deleterious consequences: first, strained areas in the glass, resulting from stresses due to unequal cooling, have a different refractive index than the glass surrounding these areas, and will thus turn light which passes through them to a focus different from that of the lens as a whole. Such light, if it falls near

the main focus, produces an overlapping blur which deteriorates the sharpness of the image. Secondly, cooling stresses will relieve themselves as the lens is ground and cause it to warp slightly, so that a true surface of revolution cannot be obtained: which leads to another serious defect—astigmatism.

Glass may be bought in slabs and in some cases this is cheaper than buying especially selected disks. The labor of making a square disk round is considerable, but to the hobbyist this would be a matter of little concern. Slab glass, in general, lacks the perfection necessary for objectives larger than 2" or at most 3". It is poor practice to economize in the purchase price of glass. The difference in price between first grade glass, guaranteed by a reputable maker, and second grade material, is not sufficient to compensate for the possible failure of the finished objective to define. One experience with a lens which, when finished, proves useful on terrestial objects alone, will convince the amateur of the truth of this assertion.

There are several sources of glass in America. Chance of England and Schott of Germany each have agencies in this country. The former is Bailey and Sharp, Hamburg, New York—the latter Fish-Schurman Corp., 230 East 45th St., New York. Bausch and Lomb of Rochester, New York, also have suitable domestic made glass available. For slab glass: L. D. Keller, 2344 North 19th St., Philadelphia, Pa. Disks are usually supplied ground round (except for a few polished flat spots on the edge, to permit the maker to test the glass) and reasonably flat and parallel on the surfaces. The optical constants of the glass are noted on a slip of paper supplied with the glass and are usually the result of accurate determination. The rough diameter allows approximately 10 percent for centering and the removal of turned down edge. Some optical glasses are more fragile than ordinary commercial plate and extra precautions should be observed to avoid chipping or worse.

Believing that an example is now in order, there follows the computation of a 4" achromat. The prescription is that it be made of a double-convex crown, followed by a plano-concave flint. Since we have decided that the first lens is to be equi-convex, fitting the curvature of the flint, we have no control over the fourth surface of the flint if the glasses are chosen first. Thus the fourth surface will come what it will. If it departs from flatness enough to be measured by mechanical means we shall make its curve to the figures.

To return: the focus of our objective is to be 15 times its aperture, or $15 \times 4 = 60''$. The glasses chosen are Schott's BK 7 and F2. The properties of the glasses are as follows:

Crown BK 7 $n_d = 1.5163$ $V_d = 64.0$
Flint F2 $n_d = 1.6200$ $V_d = 36.3$

We now determine the focus of the crown component, using the formula.

$$f_c = F \times \frac{V_c - V_f}{V_c} \tag{1}$$

and for the flint, using the formula

$$f_f = F \times \frac{V_f - V_c}{V_f} \qquad (2)$$

where: F=focus of objective (assumed to be 60")
f_c=focus of crown lens
f_f=focus of flint lens
V_f=V figure for flint glass
V_c=V figure for crown glass

Substituting in (1) we get

$$f_c = \frac{16620}{64.0} = 25.969'' \text{ crown focus}$$

Substituting in (2) we get

$$f_f = \frac{60 \times (36.3 - 64.0)}{36.3} = -45.785'' \text{ flint focus}$$

Check by reciprocals:

$$\frac{1}{f_1} + \frac{1}{f_2} = \frac{1}{F}$$

$$\frac{1}{25.969} - \frac{1}{45.785} = \frac{1}{60}$$

$$.038507 - .02184 = .01667$$

For the radii of an equi-convex lens we have

$$r = 2f(\mu - 1)$$

$f = 25.969''$
$\mu = 1.5163$

$$r = 2 \times 25.969 \times .5163 = 26.816$$

For the back surface of the flint whose front surface has a radius of 26.816" we have:

$$r_1 = \frac{r_2 \times f(\mu - 1)}{r_2 - f(\mu - 1)}$$

$f = 45.785$
$\mu = 1.62$
$r_2 = 26.816$

$$r = \frac{26.816 \times 45.785 \times .62}{26.816 - 45.785 \times .62} = \frac{761.22}{-1.57} = 485'' \text{ convex}$$

Whether this last radius is concave or convex is determined by the sign. If the result is positive the fourth surface is concave, if negative (as in this case) it is convex.

The question of color correction and allowance for thickness needs additional comment. Correction for thickness is laborious, whether it be taken care of by trigonometric trace or algebraic formula. The effect of thickness and the reason for the effect is explained as follows.

Consider a 60° prism, as in Figure 6. A ray of light *AB*, parallel to the base, is incident to one face of the prism, as shown. It will be seen that,

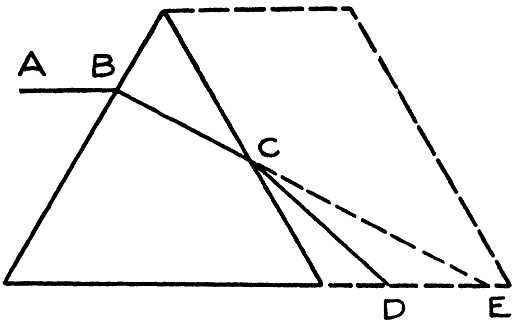


FIGURE 6

after traversing the prism, the emerging ray suffers a second refraction upon leaving the glass, in addition to the bending it underwent on entering. In this second instance it is passing from a dense to a rare medium and is bent away from the normal and meets the base line at *D*. If, however, the prism had the thickness indicated by the dash line the ray would not leave the glass before cutting the base line and would, therefore, follow the path *BCE*. It is apparent from the above, that the bending effect of a thick prism is less than that of a thin one. Since a portion of a lens may be considered a prism it follows that the effect of thickness on a double convex lens is to make it weaker, i.e., of longer focus than computed with the thickness ignored.

The formula for the focal length of a double convex lens of thickness "t" follows:

$$\frac{1}{f} = (\mu - 1)\left(\frac{1}{r_1} + \frac{1}{r_2}\right) - \frac{t(\mu - 1)^2}{\mu r_1 r_2}$$

Note that the expression $\frac{t(\mu - 1)^2}{\mu r_1 r_2}$ is subtracted from the quantity designating the reciprocal of the focal length. If the reciprocal of a quantity be made smaller, the quantity itself becomes larger—thus the focal length of a double convex lens becomes longer as it is made thicker, assuming that the curvatures of surface remain the same.

Note also that, should r_1 or r_2 be infinity (plane surface), the quantity $\frac{t(\mu - 1)^2}{\mu r_1 r_2}$ becomes zero. In other words, a lens with one flat surface has the same focal length no matter what its thickness.

For a double concave lens the formula becomes

$$\frac{1}{f} = (\mu - 1)\left(\frac{1}{r_1} + \frac{1}{r_2}\right) + \frac{t(\mu - 1)^2}{\mu r_1 r_2}$$

In this case the correction is added, increasing the value of the reciprocal expression $1/f$, i.e., the focus of the lens becomes shorter.

Thus it follows that, in an objective consisting of a double convex crown and a double concave flint, the crown focus will be longer than computed, the flint shorter and the combination will be overcorrected for color. If the flint be plano-concave this over-correction will be decreased.

Lest confusion arise as to what is meant by over and under color correction, an explanation follows:

A single converging lens will, as we have seen, bring the violet end of the spectrum to a focus nearer the lens than the red. This is said to be under-correction. Thus an objective which is corrected for color brings all colors to the same focus if the correction be perfect. One in which the blue end of the spectrum focuses at a point farther away from the lens than the rest would be said to be over-corrected—that is, the blue is pulled out too far—and conversely, one in which the blue focuses nearer the objective (as would an uncorrected lens) is said to be under-corrected.

Be this as it may, two paths are open in making a correction for the effect of thickness: by trial and error, modify (by decreasing) the radii curvature of the crown lens and substitute the e values, assuming a thickness, in the thickness formula until the focus comes out as desired; adjust the focus of the flint to suit the actual focus of the crown.

An example follows:

The lens is that computed by Ellison on page 113, "A.T.M."

		V
Crown	1.5153	60.0
Flint	1.6214	36.1

Focus of combination 90″

$r_1 = r_2 = r_3 = 36''$
$r_4 \qquad = \text{infinity (flat)}$

Focus crown 35″ (neglecting thickness)
Focus flint 58.9″

Since Ellison has indulged in some approximations which are legitimate for his purpose, we will re-compute the objective so that no question can

arise in regard to the values of the small quantities entering through our application of the thickness formula.

$$f_c = F\left(\frac{V_c - V_f}{V_c}\right) \quad \text{becomes}$$

$$f_c = 90\left(\frac{60.0 - 36.1}{60.0}\right) = \frac{3 \times 23.9}{2} = 35.85''$$

$$f_f = \frac{90 \times 23.9}{36.1} = 59.58''$$

check

$35.85 \times 60.0 = 21.51$
$59.58 \times 36.1 = 21.51$

For radii determinations:

For the crown

$r = 2f\ (\mu - 1)$
$= 2 \times 35.85 \times .5153 = 36.95''$

thus

$r_1, r_2, r_3 = 36.95''$

For the flint

$$r_4 = \frac{r_3 f(\mu - 1)}{r_3 - f(\mu - 1)} = \frac{36.95 \times 59.58 \times .6214}{36.95 - 59.58 \times .6214} =$$

$$\frac{136.8}{36.95 - 37.02} = -\frac{136.8}{.07} = -1954''$$

$r_4 = 1954''$ convex (as indicated by the negative sign). This is to all intents flat and will be so considered.

We will now assume a thickness of .7″ for the crown lens and see what happens to its focus when this thickness is considered.

Our formula again:

$$\frac{1}{f_c} = \left[(\mu - 1)\left(\frac{1}{r_1} + \frac{1}{r_2}\right)\right] - \frac{t(\mu - 1)^2}{\mu r_1 r_2}$$

The expression in the brackets is the reciprocal of the focal length as originally determined, so we have:

$$\frac{1}{35.85} = \frac{1}{f_c} = .02789 - \frac{.7 \times (.5153)^2}{1.5153 \times 36.95 \times 36.95} = .027805$$

$$f_c = \frac{1}{.027805} = 35.96''$$

In other words, the focus of the crown has been increased by 0.1″, which is obviously a negligible quantity for the work in which we are engaged.

Thus Ellison's recommendation that thickness be neglected is a good one.

Color over-correction can be eliminated in an uncemented objective by separating the components, but since our lens will be cemented we have no leeway in this direction. We can correct this condition only by making our flint lens slightly weaker—by making its back surface slightly more convex.

The great makers, however, leave their objectives overcorrected, but not, because of the difficulty of correcting for thickness. In fact, instead of bringing the C and F lines to a focus, they achromatize F and B. This has the effect of lengthening the focus for blue, and balances the under-correction existing in the eye. The eye, being a simple lens, is under-corrected for color, and tends to bring the blue to a shorter focus, as does any uncorrected converging system. For very high powers, where the pencil of light leaving the eyepiece is small, this color defect of the eye is not noticeable, and an over-corrected objective would thus show the characteristic blue haze about the image. At average powers the effects would balance and good achromatization obtain in the overall effect.

A matter which the writer has not seen called to the attention of the amateur lens maker is that of the compensating effect of thickness on color correction. We have seen that, in our type of objective, thickness has the effect of making the crown too weak and the flint too strong, thus tending toward over-correction. We said also that in an uncemented objective this defect could be cured by separating the components until a suitable correction resulted.

The reason separating the components lowers the color correction, is found in the following formula:

$$F = \frac{f_1 \times f_2}{f_1 + f_2 - d}$$

where F = focus of combination
f_1 = focus of one lens
f_2 = focus of other lens
d = distance between lenses

Let us work through an example, in order to demonstrate the effect on focus caused by separating the components. Assume a double-convex lens having a focus of 5″, combined with a double concave lens of −10″ focus. The focus, F, is to be determined when the lenses are in contact. Here $f_1 = 5''$ and $f_2 = -10''$. Substituting in the above formula we get, (since

$$d = 0) \quad F = \frac{5 \times -10}{5 - 10} = \frac{-50}{-5} = +10$$

Now suppose the above lenses were separated by 1″. We then have:

$$F = \frac{-50}{5 - 10 - 1} = \frac{-50}{-6} = +8\tfrac{2}{3}''$$

Thus the focus of the combination has been reduced $1\frac{1}{3}''$ by separating them 1″. This is the equivalent of weakening the flint lens or strengthening the crown, either of which lowers the color correction.

The above formula holds for thin lenses alone, so let us see what happens if this is not the case and the lenses have finite thickness—as indeed they must. The lenses then are no longer in optical contact, even though they may be touching mechanically, due to their thickness separating what may be called their optical centers ("principal points" is the exact term).

If, then, it be seen that thick lenses in contact are in optical effect separated, we come to the obvious conclusion that this condition has an effect on the color correction opposite to the effect caused by the thicknesses of the lenses themselves. Thus the two effects balance each other to some extent and help us to arrive at an overall focal length and color correction in accordance with the results indicated by our simplified design formulae.

Should it be desired deliberately to achromatize for B and F, the approximate method of accomplishing this would be as follows:

Returning to our friend BK 7 (Schott's list) we find the V figure for C—F given as 64.0. From the table we have the following partial dispersion values:

A—C	C—e	e—F
.00287	.00439	.00367

Assuming that B is one quarter of the distance from C to A on a wavelength scale, and that the change of dispersive power in this range is uniform, we may obtain the approximate dispersion from C to B by dividing .00287 by 4, which gives us .00071 for the value. Adding this to the C—F dispersion value we get:

$$.00806 + .00071 = .00877 \text{ dispersion B—F}$$

Now we compute "V."

$$V = \frac{\mu_d - 1}{.00877} = \frac{1.5163 - 1}{.00877} = 58.87, \text{ instead of the value 64 for C—F}$$

In a similar manner the V for F2 becomes 33.6 instead of 36.3, as tabulated.

If we now run through the computation for an objective of 10″ focus, using these new values, the effect of correcting for red will be made clear.

First let us work the example for achromatism for C and F, selecting as before, BK 7 and F2.

$$f_f = F\frac{V_f - V_c}{V_f} = 10 \times \frac{-27.7}{36.3} = -7.63''$$

$$f_c = F\frac{V_c - V_f}{V} = 10 \times \frac{27.7}{64.0} = 4.33''$$

For our new values (achromatising B and F) we get

$$f_f = 10 \times \frac{25}{33.6} = -7.44''$$

$$f_o = \frac{10 \times 25}{58.87} = -4.25''$$

Note that the crown is 1.6 percent and the flint 2.4 percent stronger than was the case for an objective designed to bring C and F to a focus. In other words, the flint has been strengthened more than the crown, which is what we would expect, since we are deliberately over-correcting.

This is a rough way to perform the operation. To do it accurately the refractive indices for B of the glasses should be known. These may be found by an empirical formula credited to Von Rohr, or better still, from the glass manufacturer—or with your own spectrometer. Which colors are selected for achromatism is a matter of opinion. A curve of the color corrections by the great masters, on page 91, Bell, "The Telescope" shows that all of them favor considerable over-correction. Lest the curve be not quite clear, note that the distance from the focus of C to G′ (in units of .00001 of the focal length) is 130 units for the Fraunhofer objective, while it is but 90 units in the Grubb (estimated by extending the curve). Thus the blue end of the spectrum focuses back of C farther for Fraunhofer's objective than for Grubb's.

If a cemented objective proves to be badly corrected for color when completed, nothing remains but to change the curvature of the back surface. An over-correction is altered by weakening the flint lens. If the fourth surface be concave, an increase in its radius will accomplish this; if flat, it will have to be made slightly convex, and if already convex it will have to be made more so. Under-correction will, conversely, be cured by strengthening the flint, *i.e.*, making its focus shorter.

This matter of the effect of the flint lens on color correction has been one to confuse some of us. If it be borne in mind that the stronger—shorter the focus of—the flint lens, the farther out the blue is thrown toward over-correction, the reasoning involved will be clear.

It is to be hoped that the color correction of our lens will come out all right, since re-grinding the fourth surface, with the subsequent repetition of polishing and figuring, is to be avoided if possible. With the excellent glass available today you may work to the C—F dispersion figures, secure in the belief that it will be well corrected. If you neglect thickness in your computation (as you should) the lens will come out slightly over-corrected and its performance will delight you.

An example by Conrady, using the "curvature" of a lens to discover its properties, is illuminating and saves time in shifting from one set of conditions to another.

The formula expressing the relation between focus and curvature follows:

$\frac{1}{f} = (n_d - 1)C$, where $C = \frac{1}{r_1} - \frac{1}{r_2}$, taking account of sign. Curves which are convex to incident light are considered plus and those which are concave, minus.

The expression for the focus of one lens of an achromatic pair becomes:

$$C = \frac{1}{f} \times \frac{1}{(V_1 - V_2)\ \delta n_1}$$

where δn = medium dispersion

The following glasses are selected and an example worked through by the above formulae.

Crown	$V_1 = 60.8$	$\delta n_1 = .00848$	$nd = 1.5155$
Flint	$V_2 = 36.0$	$\delta n_2 = .01729$	$nd = 1.6229$

Required, then, an achromatic objective having an 8″ focus and using the above glasses.

Crown: $$C = \frac{1}{8} \times \frac{1}{(60.8 - 36.0) \times .00848} = .5944$$

Flint: $$C = \frac{1}{8} \times \frac{1}{(36.0 - 60.8) \times .01729} = - 2915$$

Now

Crown: $$C = \frac{1}{r_1} - \frac{1}{r_2} \qquad (2)$$

$$C = \frac{1}{r_3} - \frac{1}{r_4} \qquad (3)$$

where the subscripts designate the first, second, third and fourth surfaces.

If it is chosen to make the crown equi-convex, then $r_2 = - r_1$ and we get by substitution:

$$C = \frac{1}{r_1} - \left(-\frac{1}{r_1}\right) = .5944$$

and since $C = \frac{1}{r_1} + \frac{1}{r_1}$ (by equation (2))

$$C = 2 \times \frac{1}{r_1}$$

$$\frac{1}{r_1} = \frac{C}{2} = \frac{.5944}{2} = .2972'' \text{ radius}$$

$$r_1 = 3.365'' \text{ radius}$$

$$\text{and } r_2 = - 3.365'' \text{ radius}$$

For cementing $r_3 = r_2$

thus $\frac{1}{r_3} = - .2972$

Hence, for the last radius, by substituting in (3)

$$C = \frac{1}{r_3} - \frac{1}{r_4} = - .2915$$

From which, since $\frac{1}{r_3} = -.2972$, we get

$$-.2972 - \frac{1}{r_4} = -.2915$$

$$\frac{1}{r_4} = -.0057$$

$$r_4 = -\frac{1}{.0057} = -175''$$

Which means that the last surface is concave to incident light (actually convex).

Now suppose we wish to change the objective so that the last surface shall be a plane. r_4 then is infinite.

$$C = \frac{1}{r_3} - \frac{1}{r_4} = \frac{1}{r_3} - \frac{1}{\infty} = \frac{1}{r_3} - 0 = \frac{1}{r_3}$$

$$\text{Thus } \frac{1}{r_3} = -.2915$$

$$r_3 = -\frac{1}{.2915} = -3.431''$$

If a cemented objective is adhered to $r_2 = r_3 = -3.431''$ and

$$C = .5944 = \frac{1}{r_1} - (-2915) =$$

$$\frac{1}{r_1} + .2915$$

$$\frac{1}{r_1} = .5944 - .2915 = .3029$$

$$r_1 = \frac{1}{.3029} = 3.301''$$

Since in our first example $r_1 = 3.365''$, it will be noted that for a plane fourth surface r_1 has a slightly shorter radius (more convex) than before.

Note also that in the above method of design the refractive index for D does not appear, but that only the dispersion from C to F ($n_F - n_C$) is used. Also the focal length for the individual lenses are not determined—though they may be, if desired, using the usual formulae.

For the sake of comparison the same example appears below, worked by the conventional method.

$$f_c = 8 \times \frac{V_1 - V_2}{V_1} = \frac{8 \times 24.8}{60.8} = 3.263''$$

$$f_f = \frac{8 \times 24.8}{36} = 5.511''$$

Check by reciprocals. And, by the way, don't neglect giving your figures a check. It is much easier to change a few figures than to regrind a finished

lens which has come out with the wrong focus because of errors in arithmetic.

.30646 — .18145 = .1250

$$\frac{1}{.125} = 8$$

Equi-convex for $f = 3.26''$

$$r = 2(\mu - 1)f = 2(.5155)3.26 = 3.364''$$

This differs by .005″ from the result found by Conrady's formula and may be ignored, since ten times this error may be expected in working to a radius.

An explanation of the maker's tables of optical glass follows:

As an example, two glasses are selected from Schott's list of Jena glass and are those usually supplied for telescope use. They are BK7 and F2.

Glass	μ_d	V_d	Medium dispersion (C—F)
Bk 7	1.5163	64.0	.00806
F 2	1.6200	36.3	.01706

Partial Dispersions

BK 7

A—c	C—e	e—f	f—g	g—h
.00287	.00439	.00367	.00432	.00356
.356	.545	.455	.536	.442

F 2

.00545	.00906	.00800	.00995	.00862
.319	.531	.469	.583	.505

Refractive indices

BK 7

C	d	g
1.51385	1.51633	1.52623
	.00008	.00018

F2

1.61504	1.62004	1.64206
	.00012	.00043

The column labelled μd is the refractive index for glowing helium gas (yellow) and not for D, the sodium line, as is the practice with English manufacturers.

The column labeled "dispersion C—F" is the so-called medium dispersion, because the colors between these lines lie in the middle of the visible spectrum. The colors of the principal lines are as follows:

A deep red
B red
C orange
D yellow
E green
F blue
G′ violet
H violet (just visible)

In Schott's tables small Roman letters d, e, g, and h are used. These denote other lines used because of the convenience of obtaining these colors in the laboratory with artificial sources of light in the spectroscope.
d is obtained from glowing helium
e, g, and h are respectively the green, blue and violet lines of the mercury arc.

To return: the column labelled V_d is an arbitrary number used by Prof. Abbè for convenience, in order to avoid the small decimals expressing dispersion. It is determined by the formula

$$\frac{n_d - 1}{\text{dispersion}} = V_d$$

Thus, for BK 7 we have $\frac{1.5163 - 1}{.00806} = 64.0 = V_d$ the value given in the table.

Partial dispersions are given for various color bands; A to C, C to e, etc. The sum of any consecutive values from these listings will give the dispersion between any lines listed. Thus, if the dispersion from C to e be added to that from e to F (.00439 + .00367), the result will be the dispersion from C to F (.00806).

These dispersion figures are the differences between the refractive indices of the glass for the colors involved. Thus, for BK 7 the refractive indices for g and C are

1.52623
1.51385

by subtraction .01238 the dispersion from g to C.

From the tables the dispersions C—e, e—F, F—g are

.00439
.00367
.00432

by addition .01238 again giving us the value g—C.

Thus, from the partial dispersions, the refractive index for various colors may be determined. Unless advanced methods of computing an objective are used, the amateur will have little use for the various refractive index values. The explanation has been included, however, for the sake of completeness.

It will be noted that below each dispersion figure another number appears. For example, under the F—g dispersion for BK 7 the figure, .536 is noted and, similarly, for F 2, .583. These figures denoting proportional dispersions are obtained by the formula.

$$\frac{F - g}{C - F}$$

For BK 7 this becomes

$$\frac{.00432}{.00806} = .5358 \text{ which the table calls } .536$$

In the design of an achromatic objective, when we bring the C and F lines to the same focus by making the focal lengths of the component lenses inversely proportional to the "V" figures for the glasses involved, these values of proportional dispersions at the blue end become important. In our little example above, the dispersion from F to g may be said to be 53.6 percent of that from C to F for glass BK 7, but for F 2 the corresponding value is 58.6 percent. That is, the proportional dispersion in the blue region for the flint glass is greater than that for the crown. A pair of lenses, therefore, adjusted for the achromatization of C and F will, because of this stronger dispersion of the flint, bring the blue-violet to a focus back of the point occupied by the focus of C and F. The flint, being a negative lens, bends the blue out more than the positive crown brought it in. This is our old bugbear, "irrationality of dispersion" and, because glasses are not available with these proportional dispersions equal, a two-lens objective cannot be made which will not leave some violet "outstanding." The effect is not serious in objectives of the small diameters with which we are concerned, but it is Prof. Conrady's opinion that many of the world's larger refractors are of questionable value because of this unfortunate state of affairs. In large instruments the colors are spread axially to such an extent that at no place may a definite focus be secured. So, if you want a 24" telescope, it is suggested that you make a reflector or, what is probably almost as easy, buy one.

Before leaving this discussion of the tables it may be remarked that Schott's tables are printed in German. However, the figures are self-explanatory and, if not, the New York agency will furnish such information as may be required. The writer has a decided weakness for their glass and, while deliberately advertising any particular maker's wares has no place in this work,* many of the larger optical firms in this country use large quantities of Jena glass, which is undeniably among the best produced. At this writing it is also the cheapest of glass from acceptable manufacturers—a point not without merit, for, at best, the material is an expensive one.

This leaves us with no further comments on the tables, except the subscript figures appended to those under the headings "refractive index for d and g." Since d has a slightly shorter wavelength than D, to obtain the refractive index for D it is necessary to subtract the subscript number from the tabular value. Thus for Bk 7

$$\begin{array}{rr} \text{ref. ind. for d} = & 1.51633 \\ & .00008 \\ \hline \text{ref. ind. for D} = & 1.51625 \end{array}$$

In a similar manner the ref. ind. for G′ is obtained by adding

$$\begin{array}{rr} \text{ref. ind. for g} = & 1.52623 \\ & .00018 \\ \hline \text{ref. ind. for G}' = & 1.52641 \end{array}$$

* Note by editor: It has been suggested to different writers in the present volume, as well as in "A.T.M.", that if a statement which it is desired to make is believed by them to represent *information which might be useful to the reader,* it should be made.

Making an Achromatic Object Glass, Apparatus and Technic

The writer agrees with Ellison that access to or possession of a lathe is an absolute necessity in the construction of a lens and its mounting. The amateur who has not this facility had best stick to reflectors.

A good optical flat is also necessary. This should be large—as an absolute minimum, not less than two-thirds of the diameter of the objective to be attempted. It should be flat to better than ¼ wavelength of sodium light.

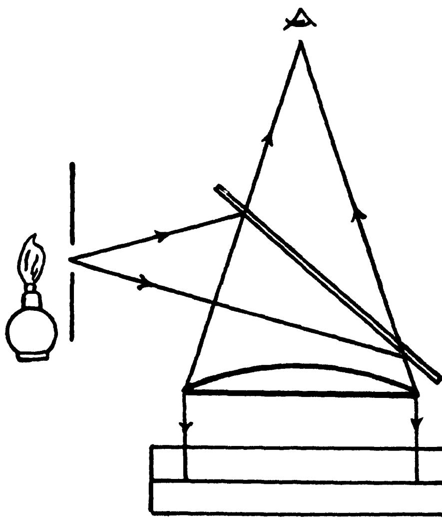


Figure 7

This is equivalent to better than ½ fringe, which is not too difficult a task in diameters under 6″, especially if Pyrex or similar glass is utilized.

Regarding the making of flats, my preference is the three plate method—assuming that no flat for a standard of comparison is available—rather than testing against a spherical mirror. The latter method is useful in the production of the large flats used in the great observatories, but is not accurate in the hands of the amateur. By the former, fringes can be definitely seen—they do not depend on the observer's judgment. With a straightedge such aberrations as may be present may easily be determined to ⅛ wavelength or better, in direction and amount.

For precise results collimated light should be used. A large lens (a "magnifying" glass will do) is mounted as shown in Figure 7, with a ⅛″ pinhole in front of the light source at its focus. Light issues from the pinhole, is reflected from the plate of glass (which is improved if half silvered on

its lower surface, but need not necessarily be so prepared), is collimated, *i.e.*, made parallel, by the lens, and falls perpendicularly on the two surfaces being tested. Returning by reflection from these, the light again passes through the lens, through the plate, and comes to a focus. The eye placed at this point will see the lens completely and brilliantly illuminated with the interference fringes plainly visible. If the collimating lens be smaller than the surfaces to be tested the flats may be moved in a direction parallel to the direction of the fringes. A straightedge, long enough to span the diameter of the flats, is laid along the edge of a fringe, and will appear to maintain

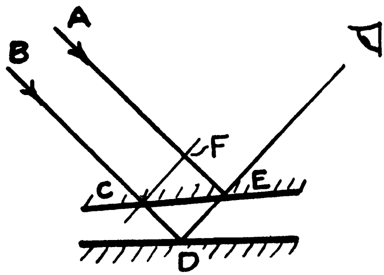


FIGURE 8

this position as the flats move—if they are flat. If this is unfortunately not the case the fringe will leave the edge, indicating a return to the lap for further correction.

In placing two flats together, especially when using a valuable standard, it is well to place three thin tin-foil spacers between the surfaces. This will avoid scratches and prevent the surfaces from molding to each other's curvature—as they will if in very close contact—and thus giving a false picture of their form.

The inaccuracy introduced by viewing the surfaces obliquely may be understood from the following reasoning: An enlarged view of two surfaces nearly in contact is shown in Figure 8. Ray *A* is reflected from the upper surface and ray *B* from the lower. If the distance *CD* plus *DE* is half a wavelength, or odd multiples thereof, greater than *FE,* the light from *B* will arrive at *E* ½ wavelength out of phase with the light from *A,* and will annul it. Thus, at all places where the distances *CDE* are equal, there will be darkness and the dark stripe thus formed is called a fringe.

Consider now, a pair of plates, assumed to be absolutely flat, placed one on the other, as in Figure 9. It is further assumed that they are in contact at *E* and slightly separated at *F*. The light source *B* and the eye *A* are on the center line also, but above the plane of the paper. The light thus falls on the surfaces and is reflected to the eye as in Figure 8. Fringes will be formed, and should be straight like the one shown. At the point *C*, however, the line of sight along *AC* will have a foreshortening effect on the distance between the plates, equivalent to lowering the eye. The line *AC,* be-

ing longer than AG, makes a more acute angle with the surface, and for the same reason our path difference CDE (Figure 8) will be longer and interference of light will therefore appear at a point nearer the eye where, due to the wedge relation of the surfaces, the path is again equal to CDE. Thus the fringe will appear to curve forward, as shown in Figure 9.

If a collimating lens is used, this condition cannot exist, since the light strikes and leaves the surface perpendicularly, and gives a true reading of the relations. If no lens is used, it is recommended that the reflecting plate be retained, since in looking down through this the effects of obliquity are reduced to a minimum. For moderate sized flats (6″ or less) or where a

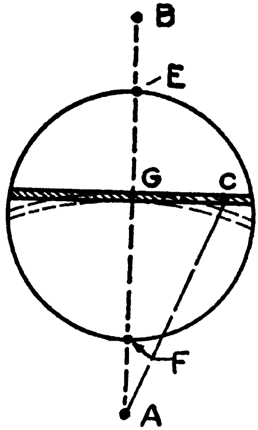


FIGURE 9

precision not better than ½ wavelength is required, the conventional method of merely viewing the surfaces in diffuse monochromatic light will suffice.

The best light source is the green line of the mercury arc. The General Electric Company makes a beautiful mercury arc lamp with a screw base, intended for street lighting, but the additional transformers necessary for its operation makes it an expensive device. They also have available a sodium vapor light of the same general construction. The Central Scientific Company (456 East Ohio St., Chicago, Ill.) has a small mercury arc which is also an excellent lamp. It has the disadvantage of requiring direct current for its operation but, since the current consumption is low, a rectifier may be built by those who are familiar with such devices, in order to permit its operation from the alternating current usually supplied to residences.

Mercury lights give the sharpest fringes when all lines but the green are filtered out. Corning Glass (The Corning Glass Works, Corning, N. Y.) has excellent filters for this purpose at not too high a price. Optically flat sur-

faces are not required on filters for this purpose, so that the cheaper grade may be used. Sodium light, being less homogeneous than that from the mercury arc, does not give as sharp a fringe, nor can interference be obtained when the surfaces are as widely separated as they may with the green of mercury light. The sodium spectrum (flame), however, consists of a pair of yellow lines very close together, and not much else. It therefore requires no filtering, as is the case with the mercury arc. Perhaps the

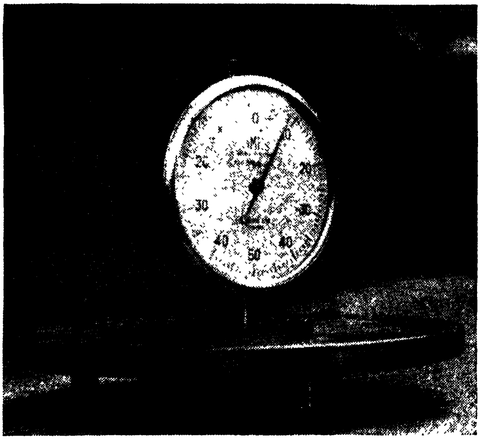


FIGURE 10

A spherometer made with a dial gage (reading, at present, .009" convex). It has a brass disk and steel legs.

bunsen flame, burning through a ring of asbestos soaked in salt, is as good as anything. It is the simplest and cheapest.

A spherometer is almost a necessity in this work, the simplest variety of which may be constructed in accordance with the photograph (Figure 10).

For the benefit of those who may not be familiar with this useful tool it may be said that the spherometer does not measure radii. The points of its three legs rest on the spherical surface to be measured, and the central point is moved until it also comes in contact with the surface. As usually made, some sort of micrometer screw is used for this purpose. The manipulation of micrometer measuring screws, however, is a delicate task, since it is difficult to judge the exact point at which the screw end touches the surface to be measured. The dial indicator solves this problem nicely. Its spindle, actuated by a weak spring, automatically adjusts itself to the surface and its pointer indicates, in thousandths of an inch, the sagittal depth. Knowing, then, that the three legs are on a circle of given radius and that the height of arc above the plane of this circle is indicated on the dial, the radius of the sphere may be computed by the following formula:

$$R = \frac{r^2 + d^2}{2d}$$

Reference to Figure 11 will make the matter clear. As will be noted, this is another form of our old friend in mirror making:

$$d = \frac{r^2}{2R}$$

The difference is that the inclusion of d^2 in the numerator is important in the case of the deep curves involved in lens grinding. An appreciable error in radius will result if this quantity is omitted from the computation.

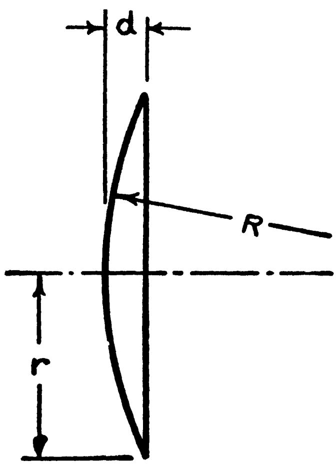


FIGURE 11

In making such a spherometer, it is important that the three legs be located accurately on the circumference of the circle selected. When turning the plate (for holding the legs) in the lathe, a deep scratch may be made with a V-pointed tool. The diameter of this may be accurately measured and, before taking the plate out of the lathe, the central hole for the dial spindle may be bored. In locating the holes for the legs the scratch will guide a center punch, so that no difficulty should be experienced in precisely positioning the legs. Precision of spacing around the circumference is not so important but will, of course, be carefully attended to by a good workman.

Since the square of the radius selected appears in the formula, a convenient number for this quantity is 1.414″, the square of which is practically 2.

The completion of the spherometer provides the first use for the optical flat, namely, setting the dial to zero (infinite radius). Place the spherometer on the flat and twist the frame which carries the graduations until zero comes

under the pointer. A magnifier is handy in setting the instrument and also in estimating fractional parts of a division when measuring a curvature. Nothing is to be gained by estimating readings closer than .0002", as the average accuracy of the gage itself is not much better than this.

And So to Work

The objective treated in this article is the type which takes the form of an equi-convex crown whose second surface fits the concave face of a plano-concave flint. Cast iron laps are used throughout, and it is for this reason that an objective having the minimum number of radii of curvature

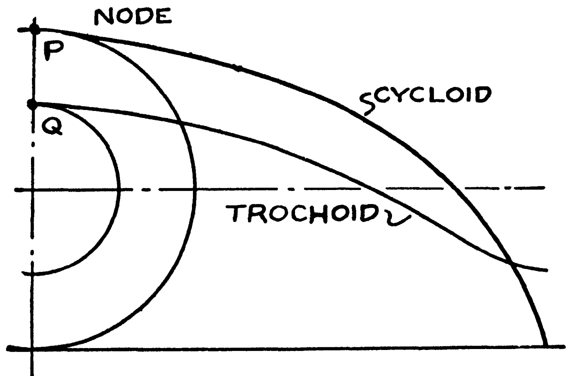


Figure 12

has been selected. Because the second and third surfaces are to have closely (not more than 10 fringes of sodium light, or $\frac{1}{10{,}000}$") the same sagittal (depth of arc) dimension, they will be cemented.

While it is not usual to cement objectives of more than $2\frac{1}{2}$" diameter, it is wholly practical to do so. Cementing annuls the second and third surfaces. It is as if the objective were a solid lens, the front portion of one refractive index and the back of another both welded into an integral piece. Reflections from two surfaces (loss of almost 10 percent of incident light) are avoided and, more important still, light reflected back and forth between these surfaces will not be brought to a focus at the eyepiece to fog the image.

Well—to work. The computation of the radii of the lens surfaces may be done in one step instead of two, as per Ellison. An example of a 4" achromatic is run through elsewhere, for the benefit of those whose algebra may have rusted up a bit.

Time is saved in rough and fine grinding by the use of metal (iron) laps. Disks of cast iron may be purchased from dealers in machine tool supplies—for example, the Victor Machinery Exchange, 251 Center Street, New York City. They cost 7 or 8 cents per pound (1935), which makes them little more

expensive than glass tools. The disk is chucked in the lathe, squeezing it no more than necessary, and the required radius turned on its surface. Since the production of a spherical surface in the lathe is a difficult matter, two devices, useful for turning iron laps, will be described. One is the classic linkage of Peaucellier, and the other a mechanism believed by the writer to be original. The latter is not mathematically perfect, as is the Peaucellier device, but in practice it has proved to be sufficiently so. It has the advantage of being more easily constructed and, having fewer components, it makes a more rigid assembly. It describes a curve known to the geometers as a trochoid, instead of the desired circle, but the central portion of this curve is sufficiently close to a circle to make the laps produced by it so nearly spherical that but little grinding is required to bring them to truth.

Referring to Figure 12, a circle is shown rolling on a straight line. The point *P* on the circumference of this circle describes a curve called a cycloid,

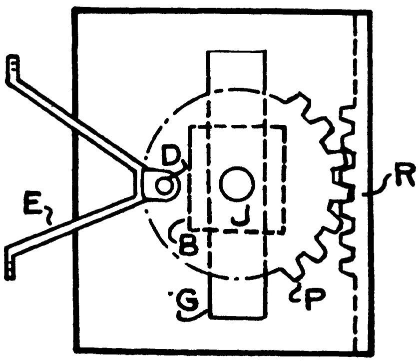


FIGURE 13

which repeats itself each time the circumference measures itself off on the line. If, instead of a point on the circumference, a point *Q* on the radius is selected and the circle rolled as before, a curve called the trochoid will be described. It will be noted that the radius of curvature of this curve at its node is longer than that of the cycloid at the same position. In fact, if the radius be shortened to zero, the moving point then becoming the center of the circle, it will describe a straight line (infinite radius) when the circle is rolled.

Having thus outlined the operating principle of the device, a design of a practical curve cutting mechanism is in order. Referring to Figure 13, a rack *R* and pinion *P* form respectively the straight line and generating circle. The pinion has its journal *J* inserted in and rigidly constrained by the bearing *B* which, in turn, is free to slide in the guide *G*. A movable radial bar is attached to the pinion, and so arranged that the pin *D* may be placed at varying distances from the center of the pinion. This pin en-

gages a yoke *E* which is attached to the compound rest of the lathe. The compound has its gibs adjusted to slide with a moderate degree of freedom and its feed screw removed or disconnected so that it may slide under the guidance of the pinion. If, then, the plain rest of the lathe be fed across the ways by its feed screw, the compound rest will follow a circular path so that the tool mounted on it will cut a spherical surface on a lap turned by the spindle. The surface produced in turning a concave lap departs from

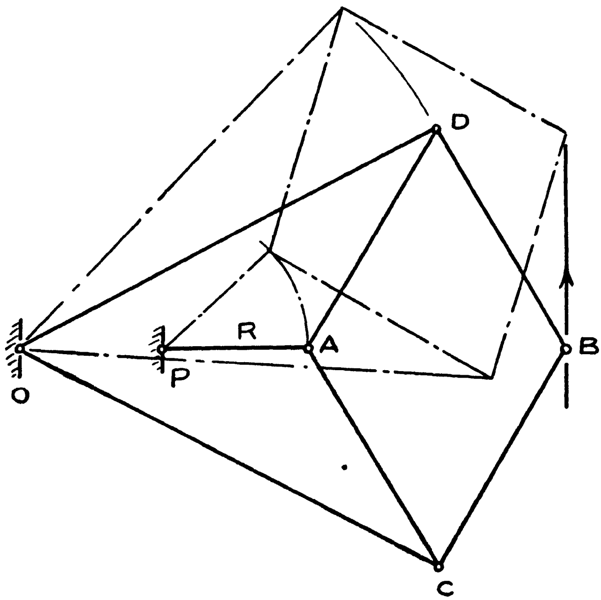


FIGURE 14

Radius described by $B = \pm \frac{OB \times R}{OA - 2R}$. *Note that, when* R = *half* OA *the denominator becomes zero and the radius described is then infinite (straight line).*

a truly spherical one by having its radius gradually shorten from center to edge, because of the fact that the point of attachment of the guiding pin is not at the point of cutting. The trochoid curve itself, also, tends to shorten its radius of curvature as it is drawn away from the axis of the lathe. Despite this, the departure from a true sphere will be in the nature of only a few thousandths of an inch in practice.

It is apparent from the figure that a concave lap will be produced when the rack is mounted at the tail-stock side of the pinion, and that a convex curve will result if the rack be placed on the opposite side.

If an electric toolpost grinder is available, a final skim may be taken off the surface of the lap, using a spherical abrasive wheel ¼″ diameter or less. This will get rid of the little high spot which is so difficult to remove from the center with an ordinary lathe tool.

The question has been asked whether cast iron laps cannot be made by rubbing two flat pieces of cast iron together with the well-known strokes and abrasive. The answer is that they may be, but that iron wears so slowly that months would be required to bring them to curve. Even changing the sagitta a few thousandths of an inch is a job requiring several hours. Glass tools had best be used if full facilities for making iron ones are not available.

Peaucellier's linkage, shown in Figure 14, will strike a theoretically perfect arc. Concave, convex, or flat surfaces may be produced, but practical experiments with this linkage, made by J. H. White, led to the conclusion that to remove the lost motion from the device was impracticable. The linkage will be described, however, in the hope that it may suggest a simpler method.

Referring to the figure, the points O and P are fixed but free to rotate, and all others are pin joints. If the point B is moved in the direction of the arrow, it will tend to make an arc by rotating about O as a center. As the linkage moves, however, link R turns on its center and pulls on one vertex A of the parallelogram $ACBD$, which opens up and pushes the point B out from the center. If link R has a length equal to half of OA, these two motions will direct B in a straight line. If R be greater than half OA, the circle described will curve to the right, and if R be less than half OA, it will be drawn curving to the left. In a practical device the link R is so constructed as to be adjustable in length, so that concave or convex laps may be surfaced.

A formula connects the radius of the curve with the link lengths. This, however, is of little use in setting the device to cut a curve. The best method is to make an approximate setting, take a trial cut, measure with the spherometer and try again. In using the spherometer, beware of the little high spot at the center of the lap. Place the spherometer on the surface so that its center leg misses this projection.*

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* A "Method of Producing Spherical Surfaces with the Milling Machine," described in *The Journal of Scientific Instruments* (London, August 1936) by S. Hariharan, M.A., M.Sc., The Presidency College, Madras, India, is especially recommended, as it is felt that this method, transmitted in the present footnote (which was added in final proof because not previously learned of), is much superior to the one just described. The quoted description is as follows:

"The method of generating a sphere described in this paper has been developed in connexion with the production of a grinding tool for a 24″ reflector mirror of 24′ radius of curvature. It was well known to the old turners of balls of wood and ivory. The only machinery used is an ordinary milling machine with practically no extra attachments. The method can be adopted to prepare both convex and concave surfaces, and the radii of curvature can cover a fairly wide range.

"If $ABCD$ be a part of the surface of a sphere, since any plane section BD of such a surface is a circle, it is obvious that a circular cylinder $BB'D'D$, which has been cut off by a plane normal to the axis, would touch the sphere all round its base. Moreover, if the sphere be made to rotate round an axis XPQ passing through the point B, the base of the cylinder would, during the rotation, touch the sphere at every point over the cap ABD. So that if the edge of the cylinder were a cutting one, it would be able to generate the spherical surface ABD. From the figure we have $CB/XB = \sin\,\theta$. If the axes intersect on the right of the plane BD, a convex surface will be generated.

"It is seen that the method of developing such surfaces, essentially requires any

Since rough grinding the lens is likely to upset the curve on the lap, unless considerable attention is paid to the matter, it is easier to rough out the lap, rough grind the lens, and bring the lap back to accurate radius on the lathe for the fine grinding operations. This has the added advantage of removing any grains of coarse Carborundum which may have embedded themselves in the surface of the iron.

Two laps are made for each curvature required, one convex and one concave to fit, unless the curvature is very flat (.010″ sagitta or less), in which case one lap will suffice. Suppose we take for example Ellison's "three-equal-curves-and-a-flat" objective. A concave and convex lap of equal and opposite radii are made and ground together. After they have been brought to the proper radius, as tested by the spherometer, and are spherical, as tested by rubbing them together after a thin stripe of Prussian blue has been "painted" on one surface, they are grooved. No grooving is necessary under 3″ diameter, but better distribution of fine abrasive and freedom from sticking is assured by grooving in the manner used with a pitch lap. A convenient tool for this purpose is a 3/32″ thick, "cut-off" Carborundum wheel on a motor-driven tool grinder. However, a file and patience will serve. The grooves are spaced 3/4″ to 1″ apart, with the center of the lap in a corner of a square (see Figure 6, page 5, "A.T.M."). The depth need not exceed 1/16″, and is unimportant. The sharp edges of the squares are rounded with a scraper and the laps are ready for use.

Jena glass is usually edged truly circular, while English glass may come irregular. In the latter case, the disks should be ground round in the lathe or edging machine, *one at a time,* and approximately the same diameter.

Since, when nearly finished, they will have to be again edged in centering, no precision regarding equality of diameter of the two disks is required at this point.

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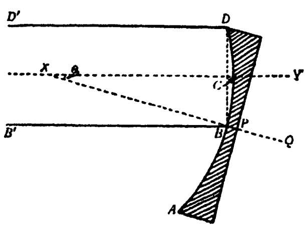
arrangement where there can be two axes, both in the same horizontal plane, the angle between the two being capable of variation over the necessary range. The milling machine with its fittings will provide all these requirements. The arbor can be removed and to the headstock spindle can be attached a cylinder, with a number of cutting points



arranged on the circumference of its circular face. This when it rotates will constitute the cutting mechanism. The dividing head can be attached to the bed of the machine and the work on which the spherical surface is to be cut can be attached to the machine's spindle and rotated at a slow speed. The necessary inclination between the two axes of rotation can be given by rotating the dividing head about a vertical axis through the necessary angle and clamping it firmly in position. All other adjustments necessary for the setting are easily provided by the machine itself."

Two holders are now to be made, to take the disks. These may be hard wood, wax-impregnated and backed with a metallic disk in order to prevent warping, or may be made of cast iron or cast lead. They are constructed like those described by Hindle, and provided with a receptacle for the grinding machine spindle if a machine is to be used. In this type of holder the glass is supported by a $\frac{1}{16}''$ annulus at its circumference and, should scratches occur, they will be covered by the cell retaining ring if any of this portion of the lens remains after re-edging for centering.

Rough grinding with iron tools is much faster than with glass, and No. 100 grit is coarse enough to start. Water is used, as is usual. It is preferable to grind the lens on top, whether the surface is convex or concave, but it will be necessary to alternate the lens and lap on top, in order that the radius of curvature of the lap will be retained. The lens is coarse ground to the required radius and not stopped short of it, as with glass tools. A convenient way to accomplish this is to turn the polishing machine spindle at the rate of 300 or 400 r.p.m., hold the lens on it by hand with plenty of pressure and stroke it back and forth, rotating it the while in the well known manner. A rough check on the edge thickness should be kept at all times, stopping the rotation of the lens to reduce the thick edge, as described by Ellison. However, after reducing a thick sector by this means, a long period of standard grinding should follow, in order to make sure that the astigmatic surface resulting from such practice is brought back to truth. Too much emphasis cannot be laid on this, as astigmatism resulting from grinding is gross and cannot be eliminated on the polishing lap.

If proper alternation between top and bottom position of the lens is made, the lap will remain spherical and hold its original radius. If not, this must be corrected either by the subsequent finer abrasive grinding or against the mating lap. Since cast iron grinds against cast iron very slowly, it is well to pay strict attention to this matter, checking the laps against each other or with the spherometer.

The lens, having one surface rough ground, is turned over in its holder and rough ground on the opposite side. It is safer to complete the grinding of each of the two surfaces with one grade of abrasive than to go through the whole gamut and, after polishing one surface, to go back to No. 100 Carbo on the other. At the completion of each grade of abrasive, tool holders, lap, lens "and all" are carefully cleaned and at no time is a coarser grade of abrasive brought near a surface finished with a finer grade. Also the iron lap goes through the grades but once, which reduces the chance of embedded coarse Carbo scratching during finer grinding. Cleaning an iron lap should be more carefully attended than is necessary with a glass tool. Ordinary cast iron is covered with tiny pits containing graphite which is, of course, soft and, unless the surface is very carefully scrubbed, may hold—alas, temporarily—a grain of coarse Carbo, to appear later in fine grinding with a ruinous scratch. Those who have access to foundries running nickel cast iron or other fine grain materials will find it worth while to avail themselves of such material.

Grinding with the finer sizes of Carbo had best be referred to the machine, but the same alternation of face up and face down for the lens is followed, and a check is kept on curvature and thickness of edge. The final fine grinding operations are as follows: one hour 303½ emery (American Optical Co., Southbridge, Mass.) or Norton lens finishing flour, followed by one hour Levigated Alumina (The Norton Co., Worcester, Mass.). To the best of the writer's knowledge, the last has the smallest grain size of any abrasive except the rouges, which are not suitable for grinding. Its use pays big dividends in reducing polishing time.

Kerosene instead of water is used for fine grinding. The abrasives cut better with this vehicle and, since it is non-volatile, it does not cool the glass by its evaporation, and distort the figure. This is a very important advantage. Everest attributes much of his success in avoiding turned-down edge to the use of kerosene. Anyone who has had the opportunity to examine one of his mirrors under test will, however, be convinced that such perfection of surface as he obtains is due not alone to this item.

It may be worth mentioning that the grain size of an abrasive is not the only criterion of performance. An abrasive with small grain size will produce a coarser surface than one with larger grains, if the latter be softer. Examined microscopically the abrasives mentioned above fall in the following order, from coarse to fine: 303½ emery; E 108 lens finishing flour; Levigated Alumina. Each has approximately one-tenth the size grain of the one preceding it. E 108 seems to give the finest finish with glass tools, Levigated Alumina with iron.

The reduction of polishing time by diligent fine grinding is very important. This is not principally because of the lessened labor, as might be thought, for this is of little moment on the machine, but because turned-down edge and zonal errors make their appearance if polishing must be continued too long. Short polishing time reduces the chance of these obnoxious features appearing. Some operators find it profitable to make an HCF lap on very hard pitch, or even on the iron tool itself, and continue "grinding" with Levigated Alumina until a fair polish appears. In preparing a lap for this purpose, after the lap is formed, smear the lens with a film of turpentine and rub it on the lap, to bring the wax to curve.

For reasons which will appear later, the second component lens is now ground and carried through to a Levigated Alumina polish.

By this time the edge thickness uniformity is of great importance, especially on the flint, whose back surface is flat or nearly so. Before going on, we digress a moment to describe methods of checking this matter. It is practically impossible to use ordinary micrometer calipers to measure the thickness of the edge of a lens. Our old friend the dial gage, however, forms the nucleus of a device that will measure this thickness and do it with precision. In fact, if desired, a lens may be ground so precisely when checked by this device that no further centering will be necessary after polishing.

Three holes, equally spaced on, say, a 3" circle, are drilled part way into a metal plate ⅜" thick, and are countersunk as if they were to receive flat-

head screws. Into the conical depressions thus formed, three steel bearing balls 3/8" or so in diameter are dropped. Two small squares or other straightedges are clamped on the plate, so that when a lens is laid centrally on the balls, its edge will come against the vertical edges of the squares. The dial gage is clamped to one square so that its spindle rests on the top surface of the lens, about 1/16" from the edge, and the reading is noted. The spindle is now lifted, the lens rotated to a new position (lift off from the balls, to avoid scratches) and returned so that its edge again butts against the straightedges. A new reading is taken on the indicator; and so on around the edge. The axis connecting the thickest and thinnest points may be marked with a china marking pencil ("grease" pencil) and the lens corrected by further grinding.

This arrangement will very accurately return the lens to position each time it is shifted, as may be checked by removing the lens and replacing it for a duplicate reading on a point previously measured. Agreement to better than .00025" may be expected.

The final check for edge thickness should be made while No. 600 Carbo is still in use. The edge tolerance should be ±.001", and better than this if possible. More than .002" is very undesirable and a great sacrifice of diameter when centering follows from a larger variation than that.

Having brought the lenses to a "polish" with Levigated Alumina, preliminary tests are now in order. A wooden cell is turned to fit the objective. If both lenses are not the same size the cell should be shouldered to fit them, so that their geometrical centers are in line. These may not be the optical centers, but will be close enough at this point if care has been exercised in keeping the edge thickness uniform. The second and third surfaces of the lens are annulled by using a liquid medium of about 1.5 refractive index. A saturated water solution of sugar is cheap, near enough optically and has the advantage of washing off readily and being non-flammable—advantages not shared by castor oil, Xylol, or Canada balsam. Glycerine may also be used.

The lens is now examined by the Ronchi test. If the surfaces are not sufficiently polished, a red filter in front of the well-illuminated slit will help. The slit need not be narrow. If bad humps or turned-down edges unfortunately are visible, the first surface should be examined by interference on the concave third surface. The flint lens is laid down with its concave surface upward, and the first surface of the crown lens is laid on it off-center and examined in sodium light. The usual fringes will form, and will be straight lines if both surfaces are spherical and of the same radius. Neither of these conditions will obtain at this time; in fact, with usual care there may be 30 or 40 fringes difference between the two surfaces. Even this variation, however, will be sufficient to examine the edge of the crown for turndown. If this edge is good, the defect must then be on the back of the flint. If the Ronchi on the assembled lens shows the edge to be very bad, it will be economical to return to fine grinding with Levigated Alumina on the iron lap. The central regions of surfaces having long radii of curvature are brought to contact with the lap with greater difficulty than is experienced

with deeper curves, especially with glass tools, and turned down edge frequently results from this propensity to stay paraboloidal. A helpful trick consists of slightly relieving the edge of the lap. The lap blank is made 1/4" or so larger in diameter than the glass which, for example, we will assume is 5" with 5 1/4" diameter cast blank. The annular area between the 5" diameter and the edge of the lap is faced off 1/64" or less below the wearing surface of the lap. This has the effect of retaining a film of kerosene around the edge, so that each time the glass projects over the edge of the lapping surface it is wetted by this film and picks up the abrasive which has been pushed off the periphery of the lap. Since difficulty in getting edge contact is partly due to abrasive running off the periphery of the lap by capillarity, the above method will be found helpful.

Assuming that gross departures have been corrected, the polishing and figuring will now be in order. Surface 3 is brought to a complete polish face down. HCF on soft pitch is used for a lap. Starting on any glass or iron tool, a pitch lap is made in the usual manner, except that the pitch may to advantage be on the soft side and formed while hot by the surface to be polished. A circle of HCF is now laid on the still warm pitch and pressed with the glass. Before the pitch hardens completely, channels are cut, as usual, although this is not absolutely essential below 5" diameter. Channels are most easily cut with a rotary knife made out of a disk of saw steel or other suitable material, mounted in a handle, like the perforating wheels which dressmakers use.

Professor Ritchey makes laps by casting tempered resin in thick strips 1" wide by 1/4" thick in a mold consisting of flat strips lightly nailed over a waxed-paper-covered board. These are removed by pulling off the sticks, and cut into squares with a hot knife. The squares are then laid in proper position on a warm tool and coated with a thin film of hot beeswax by means of a cheesecloth swab on a stick. This makes an excellent lap and avoids the difficult process of channeling, with its ever-present possibility of cracking off pitch accidentally, especially at the edge.

Well, to return—the third surface is brought to a polished sphere, as tested by reflection by the Ronchi grating. Since, in a 5" objective, the third surface may have a radius around 40" (equivalent of an $f/4$ mirror), it is important that the slit and Ronchi grating be close together and displaced as little as may be from the optic axis. When this surface is truly spherical, surfaces 1 and 2 are brought to a polished sphere. They may be tested by an exceedingly ingenious and accurate method described elsewhere by J. H. King,* or by the interference fringe method against the third surface.

The use of holders for the lenses will be appreciated long before the work has progressed this far. A handle cemented to the lenses has two disadvantages—it must be accurately centered and must be removed each time the optician wishes to look through the lens. The holders, being lathe turned,

* This test for convex surfaces is perhaps the greatest advance in testing optical surfaces since the auto-collimation method and, while some additional apparatus is required, the time expended in preparation is decidedly worth while.

are perfectly concentric and may be removed instantaneously. The danger of strain from a pitched-on handle is likewise avoided. Finally, while this statement may admit of some argument, none of the well-known objective makers of America pitch handles to their lenses.

There remains the fourth surface which, when fully polished, may be tested precisely by the auto-collimation method. The lens is "cemented" with sugar water solution (3 paper spacers around the edge of the concave surface will prevent scratches in this preliminary "cementing"), placed in its test cell, and set up in front of and as close to the flat as possible. Using a fine pinhole and ½" eyepiece, collimate the system as you would perform the same operation on a star with a completed telescope. It is important that the optical axis of the objective be perpendicular to the flat, and that the pinhole

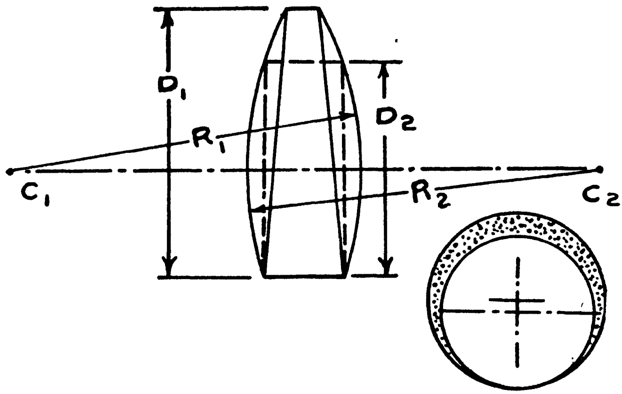


FIGURE 15

be near the focus. When the pinhole image shows no flares, and the diffraction rings out of focus (if any) are concentric, examine the figure with the Ronchi test and knife-edge. The figuring of the objective is completed by working the fourth surface.

Centering, if not already taken care of, is now in order. This is extremely important, especially in objectives which have not been computed for the best condition as regards elimination of coma. Since coma cannot in general be corrected for in an objective having equal (and of course opposite) curves for the second and third surfaces, careful attention should be given this rather fussy operation. An explanation of just what happens in centering might not be amiss, and will be made clear from an inspection of Figure 16. Centering consists of so edging a lens that its geometric axis contains the centers of curvature of both surfaces.

Figure 15 represents a lens with greatly exaggerated difference of edge thickness. If C_1 and C_2 are the centers of curvature of the surfaces described by radii R_1 and R_2, then the optical axis of the lens will be indicated by

the line C_1–C_2. It will then be clear that a crescent shaped piece of glass will have to be removed, in order that any point on the edge of the lens shall be at the same distance from the optical center as another. Unless this condition—that the geometrical center and optical center coincide—is fulfilled, the lens will have, in addition to its usual properties, a prismatic effect when light passes through it. This will disturb the color correction and, if very bad, will give an astigmatic image. The circular cut at the right of the figure, indicates by dots the portion of glass to be removed, while the

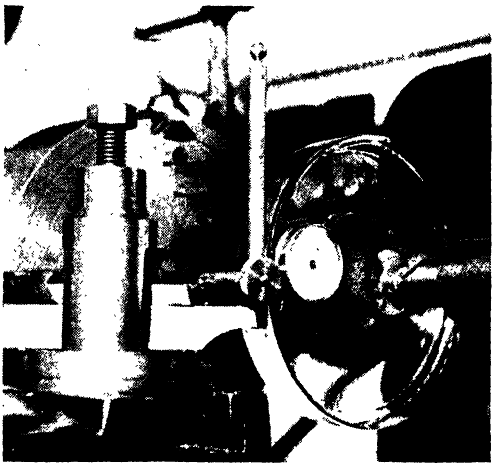


FIGURE 16

Centering in the lathe. Note brass tube not yet pitched to the disk, and sponge rubber pad holding the glass tight by pressure from the tail-stock center. The dial gage is held against the face near its edge, to measure eccentricity. The disk photographed was inserted only for demonstration.

dash lines in the main diagram indicate the cross-sectional shape of the lens after the centering operation has been performed.

Lenses which are left badly off in edge thickness in grinding will be very materially reduced in diameter when centered. It should not be necessary to reduce the diameter of a lens by more than 1/8″ in centering and, with careful workmanship, less than half of this amount need be sacrificed. Every effort should be made to get the largest diameter possible out of the blanks at hand. A 1/8″ annulus removed from the edge of a 4″ lens reduces its area by almost 10 percent—a not inconsiderable amount.

If the objective is to be permanently cemented with hard Canada balsam, centering had best be left until this operation is complete. If no hard cementing or cementing with liquid balsam is purposed, each lens will of necessity be separately centered. In either event the process is the same. The lathe

does not lend itself to centering, as too much skill is required to maintain the pitch at the proper temperature to permit the lens to be shifted on its spindle and yet not let it slide down when released. The set-up shown in Figure 16 indicates how the job may be done.

A centering spindle (which may be one of the grinding and polishing machine spindles), with its axis vertical, is best. It should be hollow and the inside hole should be 2½" or so in diameter, but may be 1" or even less. A holder which fits the spindle tightly is turned up in the lathe, heated, given a thin layer of pitch, and placed on the spindle. A piece of cross-section paper is put on the floor under the spindle and a low power telescope (2 to 6 power) equipped with an eyepiece with crosshairs, is mounted to look down the axis of the spindle. The lens to be edged is heated to 150° F. or so, by immersing it (not in contact with bottom of vessel) in cold water and bringing the temperature slowly up. It is then placed on the soft (warmed) pitch and the observing telescope focused (through the lens) on the cross-section paper. The spindle is now slowly revolved (10 to 30 r.p.m.) and the behaviour of the cross-section lines observed. If the lens is not centered (and it will not be), the lines will oscillate in the field of the telescope. Make two pencil dots on the cross-section paper, at either end of the swing as observed by the crosshairs, and move the lens so that half this distance is taken up. This may be done by rocking the lens on its spindle, or by a combination of this and of pushing it in the proper direction. The pitch should be kept soft by heating the spindle, an asbestos pad under the lens protecting it during this process. The job is a tedious and fussy one, but should not be skimped. Have the patience to make the lines appear perfectly still while the lens is rotating.

The pitch, which should be a very hard, brittle variety, is allowed to solidify when the axis of the lens has at last been made coincident with the axis of the spindle and edged by means of an iron strip with Carbo or a grinding wheel.

Since the flint lens will probably require the greatest reduction in diameter to make its edge true, it is advisable to center it first. If this is not done, it may later be found that its diameter when edged is smaller than the finished crown. This will necessitate either re-edging or having two different diameters inside the mounting cell—which is, of course, undesirable.

The crown should now be edged and should be carried, as precisely as may be, to the same diameter as the flint. The edges of both lenses should be straight and square with their axes and the sharp edges rounded. This rounding may be done by means of a Carborundum stone held by hand against the edge of the wetted glass, while the spindle revolves at a moderate speed —200 to 400 r.p.m.

The cell is now in order. This is a lathe job and had best be made of aluminum (with 8 percent copper) castings. The home foundryman will find that junk automobile crankcases are excellent material for this purpose. Where the lens cannot with safety be left in the telescope, a sub-cell to facilitate rapid removal of the objective is desirable.

The objective is placed in the cell and tested for astigmatism and centering—preferably in the telescope on a star, but a pinhole will do. A large ($\frac{1}{16}$" diameter) pinhole is observed with an eyepiece by auto-collimation. Imperfect centering will reveal itself by color in the following manner: at focus, one side of the pinhole will show a red or reddish yellow tinge, while the diametrically opposite edge will show a blue or blue-green tinge. The position of these tinges determines the axis of decentering. That is, suppose there is a red crescent which is widest at 10 o'clock and a blue one at 4 o'clock—the lenses should be shifted axially (not rotated) on each other along the diameter extending from 10 to 4; a trial will show which way. However, this unfortunate situation will not be observable if care has been exercised in centering on the spindle. If it is present, the lenses will either have to be re-centered or the cell enlarged, so that they may be shimmed to the proper position. No good mechanic will relish the latter subterfuge.

If centering is satisfactory, a real or artificial star is next in order, to try the defining power and adjust any small astigmatism that may be present. Make a small reference line with a china marking pencil, on the back surface, before assembling the objective on the telescope. A small Christmas tree ball, a globule of mercury on black velvet, or a ball bearing cemented to a thread is hung in the sun at 20 focal lengths (or more if convenient) away from the telescope, so that the sun's tiny image may be observed. Diffraction rings in and out of focus may be observed, likewise that bugbear of any optical surface, astigmatism. If the latter is present (and it usually will be, in small amount at least) rotate the crown lens a few degrees—10 or 15—at a time until the best position is found. When this is discovered, mark the crown lens over the mark on the flint. Later the edge of both lenses should be carefully grooved with a Carborundum stone, so that they may be accurately replaced in their exact relative positions, should they ever be separated.

We are now ready to cement the objective. While this may be done with hard (lump) Canada balsam,* bubbles present a real problem on objectives larger than 2½". We will therefore examine the method of cementing with liquid balsam. The material—filtered Canada balsam—consists of Canada balsam dissolved in Xylol. It should be the consistency of very thick molasses and light yellow in color, although if darker little harm will result, since the film between the lenses will be very thin. If the solution is not viscous enough, it should be thickened by adding lump Canada balsam warmed and dissolved in Xylol, warming the whole mixture in a water bath (150° F.) and stirring with a clean glass rod.

A clean cloth pad is prepared and laid on the table to receive the lenses which, having first been thoroughly cleaned, are heated to 150° F. in a water bath. Nitric acid or tri-sodium phosphate solutions are good for this, and the job should be almost as fussily done as for silvering. Dust is to be scrupulously avoided—commercially the final process is carried on under a

* Eimer and Amend (Third Ave. and 18th St., New York) or other microscope supply house.

dust-tight glass hood with "sleeves" for the workman to reach through to manipulate the parts.

If the lenses are heated while supported in a cheesecloth sling, their removal from the hot (150°–200°) water will be facilitated.

They are removed from the bath—but not until they have had time to heat through and through—and the flint, after wiping dry, is laid concave side up. The second and third surfaces should be carefully examined for possible grease spots and dusted off with a camel's hair brush.

A generous portion of liquid balsam is now poured in the center of the flint lens. If this is carefully done, no bubbles will be entrapped, but should they be present, they may be pricked with a toothpick. The crown lens, dry and dust free, is lifted in the fingers or, if too hot, with a small rubber vacuum cup (at 5 and 10 stores), such as is used to attach ash trays to auto windshields, and carefully lowered, with its orientation mark in line with that of the flint, on to the flint. If this is properly done, the center of the lens will make its first contact at the center of the pool of balsam and no bubbles will result. Large bubbles are of no importance, as these will rapidly squeeze out, but small bubbles come out slowly and should be avoided if possible. Push the lens down slowly, tilting it whenever necessary, in order to keep the widening circle of balsam approximately concentric. When the balsam covers both surfaces, continue pressing with a firm pressure. Excess balsam will ooze out around the edge in a sticky mess. Lift the cemented lenses, wipe off the excess balsam with a rag dampened (not wet) with Xylol and put the objective in its cell. This will center the lenses. Now support the back of the flint lens (not the cell) on a soft pad. Put a pad over the crown, and weight the pile heavily. (1 lb. per square inch is not too much, though one-fourth of this will do). Meanwhile the cell is, of course, in place around the edge of but not resting on the objective, in order to keep the components centered. Allow to stand for two days or bake at 150° F. for 2 hours, or both; then remove the objective by heating the cell, in order to soften the balsam which has oozed out and stuck the lens to the cell. Clean off the excess balsam as before and mount the lens in what it is hoped will be its permanent mounting. Avoid clamping the lens in any way. In placing a retaining ring, put three cigarette paper slips between the lens and ring. Tighten the ring retaining screws and remove the cigarette paper. This will leave a few thousandths shake in this direction.

It is probable that, for perhaps a day after the weight is removed from the objective, the performance will not be satisfactory. The lenses have been strained by the weight and, until the balsam yields, they will be held in this stressed condition.

The supreme test of an objective is its ability to resolve. Pick out a pair of double stars from the tables, whose separation is equal to or slightly greater than the theoretical resolving power of your 'scope. If you can find a pair having approximately equal magnitude and which are from third to fifth magnitude in brightness, so much the better. Try to separate them. If you fail on several different evenings, don't give up in disgust. The seeing

has to be good in order to give your objective a fair chance. Be sure the instrument is well collimated, as described in "A.T.M." [and the present volume.—*Ed.*] A common error is to have the eyepiece axis parallel to but not coincident with the optical axis. Make a temporary rig, in order to try this out—though with lathe-made castings and seamless aluminum tubing, this condition is unlikely to occur. However, a very slight tilt of the objective will ruin definition. Watch out-of-focus diffraction rings and fuss until they are concentric.

A word or two about observing. Shun high powers. Except for the resolution of close doubles, eyepieces of shorter focal length than 3/8" will bring up no further detail but will contribute an exaggeration of whatever defects the objective may possess. Unless a clock driven mounting is used,

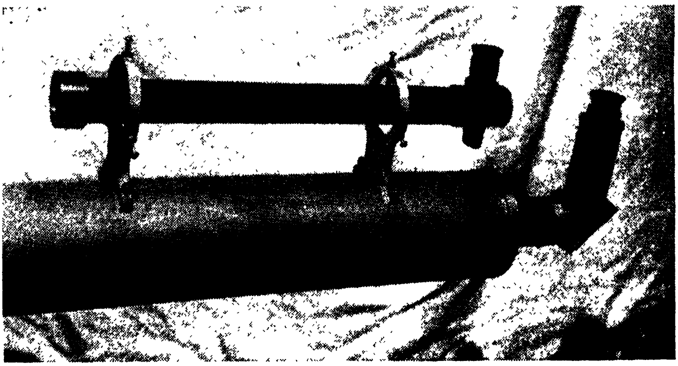


FIGURE 17

A 4½" refractor made by the author. The finder was made from a periscope.

powers above 150 diameters cannot be properly focused, because the image drifts so fast that it leaves the field before focussing can be accomplished.

In looking into either a telescope or microscope, the eye should be relaxed to focus on infinity and not adjusted to the usual 10 or 12" focus for reading. With the eyes thus relaxed the left eye may be open, unless the image under observation is very faintly illuminated. Objects in the field of the left eye will be so badly out of focus that they will offer no distraction. With this technic—a bit difficult to master at first—long hours can be spent peering into an eyepiece without fatigue or danger of permanent eye strain.

The sun is examined far less than he deserves. His ever-changing spots are very interesting and the refractor will give superior service in such observation. Place a disk of opaque paper over the objective, so that only a ½" annulus around the edge is exposed, in order to cut down the light and heat. An effective device for shunting most of the remaining light and heat off and away from the observer's eye may be incorporated in the ordinary

prism diagonal. As usually made, this device consists of a prism mounted in a box with two tubes fastened to it, perpendicular to the short faces of the prisms. One of these tubes fits in the draw tube of the telescope and the other receives the eyepiece holder (see Figure 17). If the box which contains the prism is made liquid-tight, and a screw cap with a glass window provided, the space back of the diagonal face of the prism may be filled with liquid. If this liquid is selected to have a refractive index closely approaching that of the glass of the prism, very nearly all light striking the diagonal face will be transmitted and, with its heat, will pass on out through the window. By a judicious selection of liquids, the amount of light reflected from the prism may be reduced to the point where a neutral tint cover glass

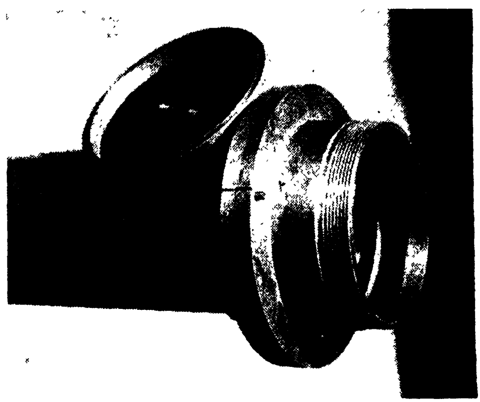


FIGURE 18

The cell, cap and retaining ring details of the 4½" refractor shown in the previous figure. Made by the author but not mentioned in the text.

on the eyepiece will be sufficient to permit observation, even with the objective open to full aperture.

The greatest caution should be exercised in making adjustments while observing the sun. If the undimmed pencil of light from the sun's image should enter the eye even briefly a permanent blind spot will be made where the image burns into the retina. It is best to work with two thin cover glasses over the eyepiece. As it is unlikely that both will crack simultaneously, the snap of one exploding from too much heat will give the observer time to wink or remove his eye.

The value of a low power telescope in observing knife-edge shadows is not generally appreciated. The magnification obtained is the least important feature of the set-up for, although this is helpful in examining the finer shadow details, the unaided eye can usually detect more than enough errors and does not require a telescope to bring them into prominence.

It will have been apparent to any who have used Foucault's method that, unless the eye be placed very close to the knife-edge, complete illumination of the objective's surface will not be obtained. As the eye is moved farther back of the knife-edge, a dark annulus appears which grows larger as the distance from knife-edge to eye increases, leaving only the central portion of the objective illuminated. A slight lateral displacement of the eye is

The author

sufficient to move the pupil partially out of the beam of light, causing a dark crescent to appear on one side of the objective.

Both effects increase in magnitude as the focal ratio of the objective under test is decreased. With ratios less than $f/6$, the eye must be placed inconveniently close to the knife-edge if the peripheral zone is to be seen illuminated.

If, however, a telescope, of from two to four power, is set up almost in contact with the knife-edge and focussed on the objective lens under test, and if adjustments are made so that the disk of the objective is seen fully

illuminated and in the center of the field, the eye may be moved about without losing the image. The convenience of this arrangement is much greater than one would believe, and its use is confidently recommended. If, as will usually be the case, the telescope is an inverting one the knife-edge should be moved into the cone of light from a direction opposite to that normally used by the optician, if the shadows are to appear as he is accustomed to seeing them with the unaided eye. Otherwise, a hump will look like a hollow, and vice versa. It is possible to confuse the use of a small telescope, described above, with the more familiar use of an eyepiece for the eyepiece test. But when examining a mirror with the eyepiece at or near the center of curvature it is, of course, the magnified image of the pinhole that is seen, while with the telescope, as with the unaided eye, it is the surface of the mirror itself which is focussed. Using the eyepiece alone, bad zonal aberrations show up clearly, while turned edge will show, back of focus, by its characteristic fuzziness.

Fortunately, in making a refractor, one is not concerned with measuring radii of curvature for different zones, but on a reflector this delicate task can also be more readily performed with an observing telescope. Whether the conventional mask with zonal openings is used, or the better "crest of shadow" method of Everest is followed, the improved visibility obtained will be found helpful.

This ends our pleasant task. The writer unfortunately does not belong to the favored few who can write with unassailable authority on his subject. He hopes that his words will stimulate an interest in building refracting telescopes and that his errors of omission and commission will be excused or corrected by those who find them.

Target Scopes

By Alan R. Kirkham
Tacoma, Washington

There are so many ways of building a telescope sight that to describe any single way is almost certain to invite hearty disapproval if not derision from various sources. However, in the following account, we shall describe a simple method which, beside requiring neither knowledge of mathematics nor tedious computation, has in practice been used to produce sights which have at least no obvious faults. It should be borne in mind that more refined and theoretically superior sights can be designed, but only at a tremendous cost in time spent in ray tracing and analytical calculation. While not extremely difficult, such computation is very complicated and time-consuming, and if the improvement is really only theoretical, its value may be questioned. Should one aspire to such things, the best recourse is to Conrady's "Applied

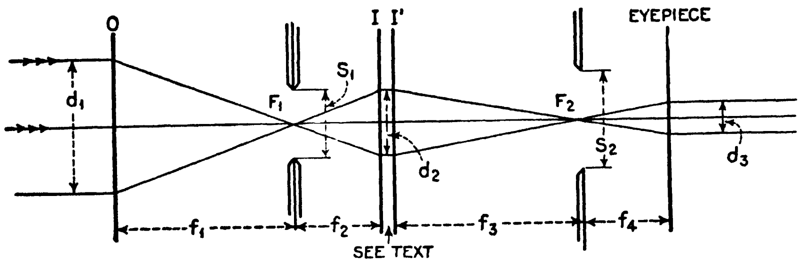


Figure 1

Ray paths through a typical rifle telescope sight.

Optics and Optical Design" or kindred treatises, of which the one mentioned is no doubt the most exhaustive.

Figure 1 shows the paths of light rays emanating from an element in the bull's-eye with the rifle expertly aimed. The rays are considered to be parallel up to O, the objective. They converge to a focus F_1, after which they diverge, falling on I and I', the erector lenses, which cause them to converge again to a new focus at F_2. At F_1 the image is inverted, while at F_2 it is erect and is viewed through a low power eyepiece. In order to have the requisite eye distance, this should be a *thin* cemented doublet. The focal lengths of the four lenses are f_1, f_2, f_3 and f_4, respectively. The erector magnification is f_3/f_2, and the focal length of the objective should be multiplied by that value, in order to find the equivalent focal length of the entire sight exclusive of the eyepiece. Calling this F, we have F/f_4 for the magnification with any eyepiece of focal length f_4. If there is a separation between the erector lenses, the distance does not count, but once worked out, a variation in their separation will result in different magnification. The use of this property in securing adjustable magnification is nevertheless at-

tended with considerable difficulty, since the whole unit must move as the separation is varied if the telescope is to remain in focus.

The exit pupil diameter is perhaps the best place to begin in finding the diameters of the lenses and stops. In general, a large exit pupil will necessitate a large objective. The exit pupil diameter, d_3, is the effective diameter of the objective, d_1, divided by the magnification. A large exit pupil is therefore obtained with low magnifications, and is desirable for hunting sights where it is inconvenient to take time in getting the eye exactly in line with the telescope. For this class of sights, 2× to 4×, with exit pupils ¼ to ⅙-inch diameter, is suggested. For target shooting, smaller exit pupils may be employed, even as small as $\frac{1}{10}''$ to $\frac{1}{12}''$, which makes higher powers obtainable. The apparent field of view is about equal to the stop diameter S_2 seen

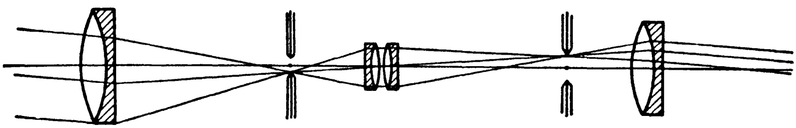


FIGURE 2

at the eye distance. The diameter of the eyepiece should be equal to the stop diameter plus the exit pupil diameter. The erector lenses should be f_3/f_4 times the exit pupil diameter, after allowing a rim for mounting. If they are separated somewhat, make them a trifle larger and put a stop of that diameter between. The diameter of the stop S_1 is now f_2/f_3 times that of S_2. The objective diameter is given by

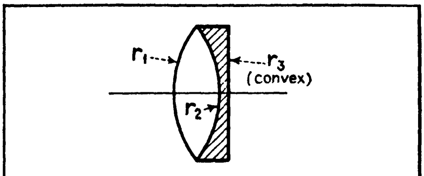
$$\frac{f_1}{f_2} d_2 + \frac{f_1 + f_2}{f_2} S_1$$

The first part of the expression gives the "effective diameter" mentioned above, while the second part is that which is added for the displacement of the cones of rays from objects at the edge of the field, as shown in Figure 2. The width of any field w, at a distance D (*i.e.*, to a target), is $w=(S_2/F)D$, to a close approximation. Curvature of field depends directly on the focal powers of all the lenses added together, hence very short focus lenses are to be rigorously avoided in any design.

Figure 2 indicates how the lenses should be turned, and also shows the paths of light rays from an object at the edge of the field. Figure 3 gives the construction of each lens. The hatched component represents ordinary flint glass of refractive index 1.615, and dispersion 36.6. The convex lenses may be made from borosilicate crown glass of refractive index 1.517 and dispersion 64.5, or of barium crown having an index of refraction 1.576 and dispersion 57.3. The radii for an aplanatic lens are given in the table in Figure 3, and have only to be multiplied by the desired focal length to obtain working data. The first row is for borosilicate crown and dense flint, as above, and the second is for the barium-crown-dense-flint combination, which has some-

what better color correction, and a considerably flatter field. The barium crown is not as durable, however and requires making more laps.

The actual grinding and polishing of small lenses is well described by Porter in "A.T.M." and in the present volume. The eyepieces may be mounted without any tests. The objective and each component of the erector should be tested, with crowns facing the light, by the method given in "A.T.M." near the bottom of page 444. The curving of the Ronchi bands, indicating hills or hollows, should be interpreted exactly opposite to the descriptions given in the chapter on the Ronchi test, "A.T.M.," which apply to mirrors. The objective may be figured by making a little pitch tool on a board, and polishing by hand in such a manner as to hit the high spots. The erector lenses are seldom much over a half inch in diameter, and will nearly always be found perfect if made with reasonable care. Should a distinct error be found in one, it will probably be best to regrind and polish it. Before testing,



	r_1	r_2	r_3
1	.425	.425	10.00
2	.636	.309	2.825

FIGURE 3

the lenses should be "dummy-cemented" with glycerine, to take the place of the balsam which will finally be used. Figuring done on cemented surfaces is practically without effect. Try the crown both ways (if it is equi-convex) and leave it the way it will require the least figuring. When the errors are all removed, and the Ronchi bands are practically straight, the lenses are ready to be balsamed together.

The balsam sold by most opticians, for cementing microscope cover glasses to slides, is satisfactory. Clean the lenses absolutely spotless, put a drop of balsam on the flint, and lower the crown squarely over it. Finally press them together, being careful not to let them slip around on one another, until all surplus balsam is squeezed out of the edges, which may be wiped clean frequently with a rag *barely moistened* with xylol. The lenses are then baked for three or four hours at a temperature just above what the hand can bear.

Little will be said about the mounting (Figure 4), since it would be almost futile to attempt the job without some knowledge and skill in mechanics. The mounting presents nothing unusual in the way of lathe work, but the lenses should be rather firmly mounted, with quite a wide rim for a seat, in order to withstand the recoil. The reticule is situated at the focus of the eyepiece, and should be adjustable to and from it, for parallax. Focusing

may be accomplished by moving the eyepiece and reticule together, or by moving the erector lenses as a unit, the latter being the prevailing practice. The reticule could be moved by screws or levers for windage and elevation.

Two questions are likely to arise. First, how much distance should be allowed between the erector lenses, if they are separated? Separation of the lenses a certain amount is supposed to improve the color correction under some circumstances, though it has other effects, both good and bad. Practically, it seems to make little or no difference, and the builder may suit his whims, up to half or three quarters of an inch. Secondly, the designer is almost sure to find that the exit pupil diameter and the magnification he picks in the beginning, will require an unreasonably large objective. This

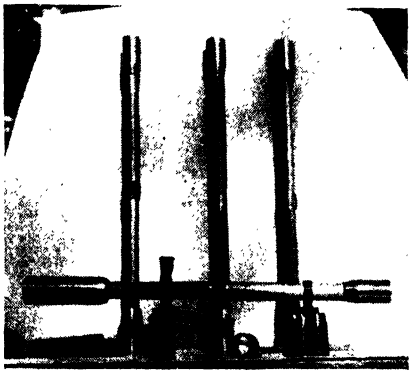


FIGURE 4

Four rifle sights made by the author. Their mounts—attachments to the rifle—which show at the bottom, are by Lyman.

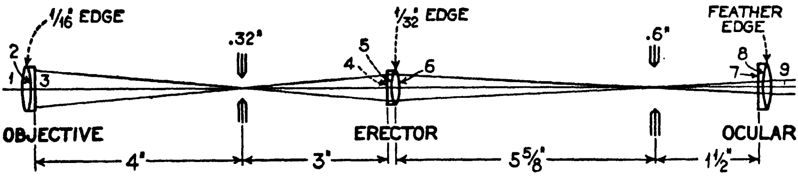
is a far more important consideration than the first. Since the second part of the formula given for the objective diameter depends alone on the width of field, this is another reason for not trying to obtain extremely wide fields. One should make careful drawings, after the plan of Figure 2, and study them in order to deduce what changes can be made.

Of course the formula mentioned represents the ideal, with which all parts of the field will be equally bright. Obviously, if all of the rays, when traced backward (as in Figure 2) from the stop at F_2, do not succeed in getting through the objective, the only effect will be a slight diminution of brilliance at the edge. With large exit pupils, one could afford to lose perhaps half of the light at the extreme edge of the field, and the effect would not be detectable to a casual user.

It is necessary to cut and try, in designing these systems, and one is almost always forced to make compromises either in the brilliance or the edge of the field or its width, if he is to obtain either large exit pupils or wide

fields. It is often difficult for the layman to realize that these systems are always designed either by whim, or by an ordered effort along experimental lines, in order to obtain desired ends, and that there are no magical formulas which will answer the question, "What kind of sight do I want?"

[EDITOR'S NOTE: Unlike the other chapters the present one will be used chiefly by readers who have not had previous connection with telescope making—riflemen who wish to build a target or rifle scope, rather than amateur telescope makers who wish to take up target shooting. If a telescope maker wished to take up target shooting, and desired to make his own target scope, he would bring to the work the experience he had previously gained in making reflectors, probably refractors as well, and other optical



Objective

CROWN N_D = 1.5101"
V = 60.4"

FLINT N_D = 1.6183"
V = 36.6"

DIAM. 3/4" (5/8" CLEAR)
r_1 = +1.6"
r_2 = −1.6"
r_3 = ∞

Erector

CROWN N_D = 1.517"
V = 64.5"

FLINT N_D = 1.6183"
V = 36.6"

DIAM. 9/16" (1/2" CLEAR)
r_4 = +2"
r_5 = +0.66"
r_6 = −1.2"

Ocular

CROWN N_D = 1.5101"
V = 60.4"

FLINT N_D = 1.6150"
V = 36.6"

	1½" f.l.	2" f.l.
r_1 =	+2"	+2.6"
r_2 =	+0.57"	+0.78"
r_3 =	−.9"	−1.2"
EYE RELIEF =	2"	3"
DIAM. =	3/4"	7/8"

Drawing by J. F. Odenbach, after the author

FIGURE 5

Scale drawing of a specific rifle sight, with specifications. Data by the author. The erector moves about ⅛" for parallax adjustment. The ocular should be movable, in order to adapt the telescope to the eye of the individual. The magnifications obtained, with the eyepieces indicated in the table (lower right) are x5 and x3¾", respectively.

gadgets. But how should the rifleman, lacking this previous experience, proceed to do the job? If he were clever he probably could go right at it, after studying parts of the present volume, or of this and "A.T.M." See, in the present volume, Porter, also Clark, on small lenses, and Haviland on the refracting telescope; in "A.T.M.," Porter on making eyepieces and especially Ellison on the refracting telescope (the Haviland chapter in the present book covers the same general ground as the Ellison chapter in "Amateur Telescope Making," but in a more advanced and probably for this purpose an unnecessarily refined manner since a terrestrial telescope does not ordinarily require the same precision as one for astronomical work). If at the end of

this survey the subject still seems a bit misty, perhaps this means merely that he should have done some preliminary optical work of a less specialized kind, such as making a refractor of a more ordinary type. For this, why not select a spotting scope, such being a typical small refractor, just the beginner's size for an amateur telescope maker, in fact, or about 2″ aperture.

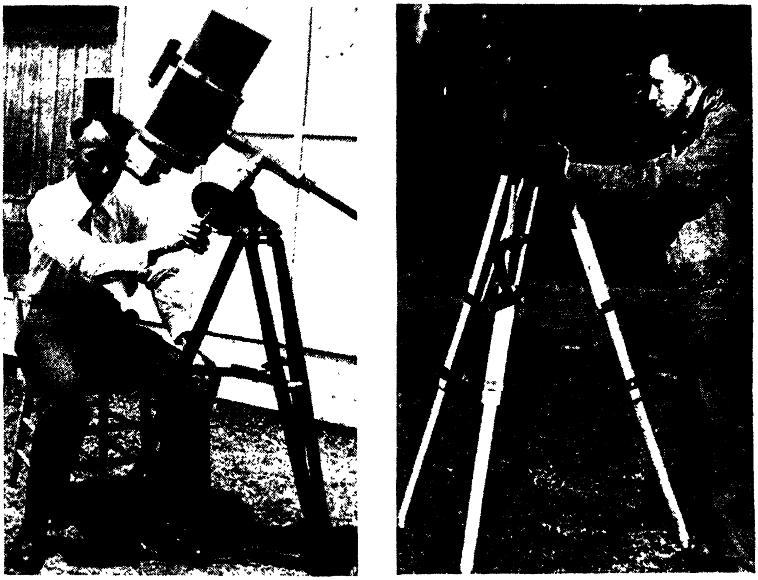


FIGURE 6

Left: Harold A. Lower of San Diego, California, with a 7″ astronomical Cassegrainian reflecting telescope. In such types the path of the light rays is in effect folded up, so that a telescope about 5′ long is compacted into about 18″ length. The owner states that it is also used at turkey shoots and shows bullet holes in the black at 200 yards when the light is poor and many other spotting scopes with less light grasp—smaller aperture—will not show them. However, he adds, this is only when there is no mirage. When there is mirage the 3.20″ refractor shown at the right is probably as large as can be used satisfactorily under usual rifle range conditions. Moreover, on the whole, reflectors are not recommended for range spotting. Resolving power is also reduced in daytime. Right: The B. and L. Team Captain's scope with 3.20″ objective lens and changes of eyepiece giving powers of x12.7, x21, x25.6 and x32.6.

But the beginning amateur telescope maker seldom cuts his teeth on any refractor, as the objective in it has four surfaces to work and this is tedious. He usually starts on a reflector, since the roots of any refractor job will be found running back into mirror making. So it may, after all, pay to begin at the beginning—though quite a long detour merely to gain a target

scope, a spotting scope, and a reflecting telescope which he probably doesn't want, anyway.

Well, if he is to get nothing out of it but the two or three scopes he has made, perhaps he had best buy them and be done with it. If, however, he enjoys creating his own things, and can possibly get some use out of the astronomical scopes made primarily for practice, then let him go to it. One thing seems fairly certain: a rifleman who had made his own spotting scope and target scope, including the lenses, and picked up the science of lens designing and the art of lens making, would have and of a right ought to have the privilege of wearing his chest well out in front when on the range. And the chances are that many a keen, practical man will be able, after a few false moves, to short-circuit most of the apprenticeship outlined above by doing the job without it.

To the amateur telescope maker who has had no experience as a rifleman, the following data may be of interest. Spotting scopes are usually refractors of small aperture—about 1½" to 2"—with an erecting eyepiece and mounted on a stubby little tripod which is placed near the rifleman whereever he lies prone. They are used to examine the target. Take, for example, the B. and L. descriptive literature. A spotter described in it has a 45mm. (about 1¾") O.G. and magnifications $\times 12$, $\times 19.5$, $\times 26$, $\times 36.5$. Another is the team captain's scope shown in Figure 6, at the right—a photograph furnished by Bausch and Lomb. With this the team captain quickly picks up different targets.]

Testing Convex Spherical Surfaces *

By J. H. King
Amityville, Long Island

Concerning the polishing of convex spherical surfaces, Ellison states in "Amateur Telescope Making," 'No question of their figure can arise at this stage of the proceedings, as it is impossible to test it.' Professional makers sometimes test convex spherical surfaces by interference methods, referring the convex to a standard concave. This method is hardly practical unless a number of similar convex lenses are to be made.

Judging from the number of times the desire has been expressed for a test for convex lenses which would be as simple as that for concave mirrors, it would seem that such a test, if available, would be very useful. Therefore, the writer proposes a test for convex spherical surfaces requiring no auxiliary optical surface, and one which is simple and as rigorous as the mirror test at center of curvature.

If, for the sake of illustration, we imagine a spherical surface consisting of only a skin of silver of practically no thickness, which would at the same time remain optically true without support on either side, one side would be a convex mirror and the other a concave of the same radius. Then, in order to test the convex mirror, one would merely have to go around to the other side and test the concave at the center of curvature.

However, practical optical surfaces are generally formed on glass but if, as in the case of convex spherical surfaces on lenses, we could eliminate the lens optically and leave the surface to be tested, we could again go around back of the convex and test it as a concave mirror at the center of curvature and that test would be the equivalent of a test of the convex surface.

To do this, we make use of a simple principle employed for many years in inspecting optical glass, but to the writer's knowledge never applied in this manner. In examining optical glass for striae and general uniformity of index, when it is in crude broken chunks, it is placed in a large container having glass windows at either end. Liquid is introduced having the same refractive index as the glass and then, if the glass is homogeneous, one is able to look clear through the liquid and the chunk of optical glass, and the rays will suffer no deviation. In other words, we have optically eliminated the glass. Bell's "The Telescope," page 61, gives an account of this method of inspecting optical glass.

Figure 1, at the left, shows a sectional view of the set-up which allows us to test a convex as a concave by introducing a fluid equal in refractive index to that of the glass. The fluid optically eliminates the lens. Since the upper convex surface faces air, the light proceeding from the pinhole suffers a partial reflection and some of it returns to focus again adjacent to the pinhole and the test becomes merely that for a spherical mirror at

* First published in Scientific American, Feb. 1935, page 100.

center of curvature. The test is rigorous because it is conducted to all practical purposes entirely within the liquid medium, and the small amount of air between the eye and the window is too close to focus to be detrimental. Several solutions have come to the writer's attention as having about the refractive index of crown glass when near room temperature. Toluene [obtainable from dealers in chemicals; for example, Eimer and Amend, Third Avenue and 18 Street, New York City.—*Ed.*] seems to be the best commercially obtainable liquid, since it is homogeneous and, though inflammable, does not have a low vaporization temperature. A very strong word of caution should be urged against the use of benzene or any other

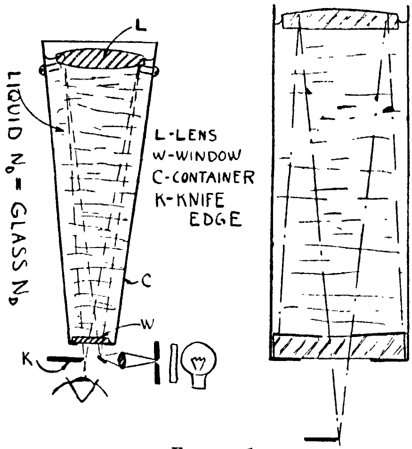


FIGURE 1
The King test.

inflammable liquid which vaporizes at room temperature. The worst explosion due to chemical silvering would be very mild indeed compared with that due to a gallon of benzene properly vaporized and ignited in a closed cellar.

Below is given a list of various liquids and their refractive indices for the sodium line at given temperatures. However, the refractive index usually does not vary widely with a slight change in temperature.

Aqueous Solutions (Sugar and Water)

Sugar—Refractive Index at 20° C.
1.5001 at 16 percent water
1.5033 at 15 percent "
1.4951 at 18 percent "

Non-Aqueous Solutions

Carbon tetrachloride 1.460 at 25° C.
Benzene 1.501 at 30° C. (Dangerous)

Aniline 1.586 at 20° C.
Glycerine (Glycerole) 1.474 at 25° C.
Toluene 1.495 at 20° C.
Carbon tet. 40 percent, Ethylene bromide 60 percent, 1.4989 at 25° C.

Aqueous Salts

Pyradine 85 percent, H_2O 15 percent, 1.4960 at 15° C.
NaCl 20, KCl at 80 percent, 1.500, 18° C.

Some may raise the objection that the dispersion of the liquids may not be equal to that of the crown glass. Of course, testing in sodium light would remove this objection completely, but the writer believes that testing with white light is about all that is necessary and the refractive index does not have to be exactly that of the crown. This has also been borne out by experiment.

As a matter of convenience, a small prism may be used in place of the window, and the testing funnel mounted on a wall. This allows the observer to assume a comfortable posture looking horizontally instead of lying on his back as in the left-hand drawing, Figure 1.

This principle is also applicable to testing a convex hyperboloidal surface by using a small spherical mirror of scarcely larger dimensions than the convex hyperboloid. The right-hand drawing shows the set-up. The spherical mirror should be silvered and lacquered and the silver removed in the center, leaving a small transparent hole. Using this method, it is not necessary to construct a large optical flat or a large spherical mirror when building a compound telescope of the Cassegrain type. However, it would be well to construct the small secondary hyperboloid of optical crown in order to insure freedom from striae.

[EDITOR'S NOTE: Shall the test described above be called the King test?]

Collimation and Adjustment—a Composite Chapter

Collimation. By J. V. McAdam, Hastings-on-Hudson, N. Y.: *A, B* and *C* (Figure 1) are cardboard disks with ¼″ holes at center, covered with tinfoil having ⅛″ holes at center.

D is a tube 8″ long—cross-hairs at one end, head in other end, with 1⁄32″ hole. Head line with white cardboard having ⅛″ central hole. Window in side of *D* to illuminate cardboard.

Remove prism and mirror. Line *C* up with *A* and *B* at about center of curvature of mirror, by sighting through *A*.

Remove *A* and *B* and insert prism, mirror, and *D*.

Adjust mirror to cast image on *C*, concentric with pinhole. This brings axis of mirror absolutely to axis of tube.

Adjust prism to bring spot in center of mirror, cross hairs in *D* and

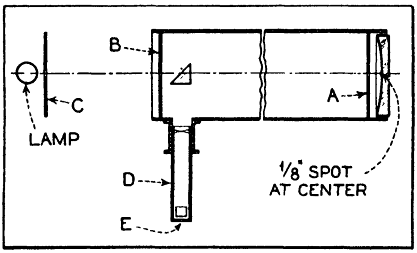


FIGURE 1

image of *E* reflected from face of prism exactly coincident. This brings faces of prism square to mirror axis and ocular axis and insures rays converging on ocular being symmetrical about ocular axis.

All parts should be securely clamped into position to prevent movement during adjustment.

Collimation. By Chas. W. Eliason, Chicago, Ill.: It would seem to me that a really high order or precision in adjustment is necessary for the use of high-power oculars, at least. The field stop of a one-fifth inch eyepiece, for example, is rather less than one-eighth of an inch in diameter, and the job is to turn the axial pencil of the objective into this narrow opening. Since critical definition falls off so rapidly away from the axis, this is exceedingly important, and I have thought that the sometimes disappointing performance of amateur objectives is due to failure in this regard.

A good many of the books on the subject suggest checking the collimation by racking out the eyepiece and observing whether or not the out-of-focus images are circular. If this is done, a moderately high-power eyepiece should be used, to give a fairly small ocular circle. A low-power eyepiece will emit so thick a bundle of pencils as to fill the lens of the eye, and any defect of vision will show up in the out-of-focus image. In my own case,

a one-inch ocular gives me remarkably astigmatic images. Of course, the axis of the astigmatism will rotate if the head is moved a bit, but I was firmly convinced for a long time, in consequence of this phenomenon, that my principal mirror was hopelessly warped.

The alinement of the prism of the Newtonian is a matter of some difficulty. Accuracy is important to performance, however, and pains will be fully repaid in better definition. The following method is offered as a substitute for the rough procedure usually suggested:

It is presumed that the prism is so mounted that it may be conveniently adjusted. It is also assumed that the prolongation of the axis of the eyepiece adapter intersects the axis of the telescope tube, and at right angles. Fitments that do not permit easy motion in all required directions are a sore trial to patience. Possibly the best arrangement is the familiar one of supporting the prism by means of four webs terminating in slotted holes

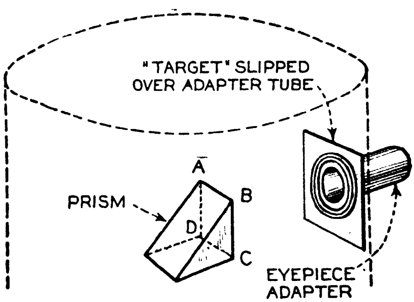


FIGURE 2

in the wall of the telescope tube. If the prism can also be rotated around the axis of the tube, the adjustments are complete.

The prism is first centered with respect to the telescope tube. This can be done with sufficient accuracy by measurement. It is also adjusted so that it is roughly central to the adapter opening, judged by looking through the eye end.

A "target" is now prepared. A hole large enough to fit snugly over the inside end of the adapter is cut from a white card, and heavy black concentric circles, about 1/8" apart, are ruled outside the cut-out "bull's-eye." This card is slipped over the inside end of the adapter, facing the prism. (See Figure 2.)

If the cell end of the telescope tube is now covered with a dark cloth (the mirror having been removed), it will be possible to see, on looking into the adapter, a faint reflection of the target in the nearer *square* face of the prism, (surface A, B, C, D, in the drawing). An eyepiece, lenses removed, should be slipped into the adapter for this purpose. Adjustment of the prism is now made, so that the reflected system of circles is centered on the

square face of the prism. This is easily done by moving the prism until one of the circles is tangent to all four edges.

For the dark cloth over the cell end of the tube, another is now substituted which will admit enough light so that the circular opening of the tube can be seen reflected from the hypotenuse side of the prism. With a little juggling of the illumination, it will be possible to keep the reflected circles of the target still in view.

The adjustment is now completed by moving the prism up or down the axis of the telescope until the image of cell end is concentric with the system of circles reflected from the target, *the latter being, at the same time, kept centered in the square face of the prism.* This requires some sleight of hand, but the trick is soon learned.

No attempt should be made to center either the reflection of the target or the image of the end of the tube in the hypotenuse face of the prism as seen through the adapter. Neither, when the adjustment is perfect, is centered in the hypotenuse face, as a little geometry will show.

The principal mirror is now collimated by its own leveling screws, using one of the usual procedures, and the job is done.

Adjusting the Polar axis. By Cyril G. Wates, Edmonton, Alberta: The adjustment of a telescope mounting, either by the Pole Star or by following the movement of an equatorial star, is a long process which may consume several nights' work and unlimited patience. The method to be described is suited only for telescopes having setting circles, but when such circles are provided, the necessary adjustments can be completed quickly and accurately. It is assumed that the tube has been lined up at right angles to the declination axis by the usual method, and that the optical parts of the telescope are in their proper relationships.

Consider the following theorem: If two spheres are brought together so that any three points on one sphere coincide with the corresponding points on the other, the spheres are identical. The two spheres in question are the celestial sphere, and a purely imaginary sphere rotating upon the polar axis of the telescope and equal in size to the celestial sphere. The various parts of the celestial sphere are marked by the stars. The corresponding points on our imaginary sphere are determined by the setting circles.

Therefore the theorem above can be re-worded to read: If the telescope be so adjusted that the position of any three stars is correctly indicated by the declination circle, the polar axis is correctly adjusted.

To put this theory into practice select any three stars. The first should be about one hour east of the meridian at the time when you propose to start work. The second should be in the east or south-east; the third in the west or south-west. These three stars will be designated by the letters *M, E* and *W*. Look up the declination of all three stars and make a note of the figures. It is desirable but not absolutely necessary that all three stars should be near the celestial equator. Bright, easily found stars are the main requirement.

Set the telescope so that star *M* is in the center of the field, and move

the declination circle or its pointer to the correct reading for that star. Now move the telescope on its declination axis until the circle indicates the correct declination for star *E*. Swing the telescope around in the direction of *E* and note carefully whether you must move the tube north or south to bring the star into the center of the field. Repeat the performance with star *W*, and again note the direction in which the tube must be moved to correct any error. Record your results like this—

E—South *W*—North

and compare with the following table:—

Star E	*Star W*	*Move Polar Axis*
South	South	Raise
North	North	Lower
North	South	West
South	North	East

The directions in the last column refer to the top end of the polar axis. Raising and lowering is done by means of the usual adjustment screws. East and west movement means turning the entire mounting, or tilting the axis by moving one screw, if two are provided.

The tests and adjustments are repeated until all three stars give correct readings on the declination scale, when it is obvious that the theorem is satisfied. Final adjustments are best deferred until star *M* is exactly on the meridian.

In the case of mountings which require the tube to be swung across to the opposite side in crossing the meridian, the preliminary setting is best accomplished by selecting a star very close to the meridian and reading off the Dec. on both sides—that is with the tube on both sides of the Polar axis. Naturally, the readings should be alike, and the mounting should be tilted north or south until the readings are the same. Then proceed as above.

Indoor adjustment of an Equatorial. By F. R. Varela, Tenafly, N. J.: While building an equatorial telescope mounting, a very simple method of making indoors all the necessary adjustments was worked out, with the exception of the final meridian setting of the instrument to make it ready for use. The method is applicable to an instrument with the following equipment or its equivalent: setting circles, slow motions, leveling screws, levels in meridian and prime vertical planes. It is also assumed that the polar and declination axes are perpendicular to each other, and that the optical system has been adjusted to its final setting and there made secure against accidental derangement.

The method is as follows:

(1) On a concrete or other substantial floor, set instrument approximately level.

(2) Raise polar axis approximately to correct elevation for latitude.

(3) Set telescope tube parallel to polar axis and directly above it, and clamp both slow motions.

(4) Adjust hour circle to read VI hours, and set it.
(5) Adjust declination circle to read latitude of the place, and clamp it.
(6) Swing telescope to right side of pier and set line of sight to the nadir.
(7) Read both circles as accurately as these will permit.
(8) Swing telescope to left side of pier and set line of sight again to the nadir.
(9) Read both circles as before.
(10) Take the difference between the declination circle readings and subtract it from 180, dividing the remainder by 2. The resulting angle is the actual elevation of the polar axis. This is equal to the latitude of the place, plus or minus the error in the original setting. Call this error *a*.
(11) By means of the slow motion in declination, move the telescope in the proper direction by this angle "a," and by means of the leveling screws bring the line of sight again to the nadir.
(12) Repeat the process till the residual error disappears, and set the declination circle to read the co-latitude of the place.
(13) The mean of the hour angle circle readings will give the true location of its zero point.
(14) A re-check will show whether the two zero points (or the 0 and XII points) of the hour circle are true in both positions. If not, the error is probably due to lack of perpendicularity between the line of sight and the declination axis. While the value of this error can be computed, it is perhaps more practicable to try inserting a shim between one end of the saddle and the tube. This will indicate which end of the saddle is high and by approximately what amount. When your hour circle readings finally check, your circles are correctly set.
(15) Finally, without disturbing the telescope, adjust the level bubbles by their own adjusting screws (not by means of the instrument leveling screws) to the center of their runs.

While, with reasonable comfort and abundant light, we have made practically all necessary adjustments indoors and without reference to the stars, we have not thereby disregarded astronomy in our process. Indoors or out, the force of gravity has been our point of reference.

Several points of considerable importance remain to be mentioned, of which all but one are self evident. Among these, the level bubbles must be of fair quality and of a sensitivity of about 60 seconds of arc per division (usually 2 mm.); the mirror and prism (or the lens cell in the case of refractors) must be capable of permanent adjustment.

The manner of setting the line of sight to the nadir, or plumb line, has not, however, been explained. One very reliable method is by bringing a set of cross-hairs to coincide with their image from a mercury surface set below the telescope. While beautifully accurate, it has the disadvantage for the amateur astronomer of the high cost of the mercury and the difficulty of properly illuminating the cross-hairs.

One method, which is capable of considerable precision, is to attach two

small pieces of brass angle to the two ends of the telescope tube. These angles are each provided with a peep hole about $\frac{1}{32}''$ in diameter and, when attached to the telescope tube, should be set parallel to the line of sight by setting the cross-hairs on a distant street light, 1000 or more feet away and lining up the two peep sights, by sighting through them on the same object. If the distance between the line of the peep sights and the mirror axis is, say $5''$, and the light sighted is $1000'$ away, the error will be less than $1\frac{1}{2}$ minutes of arc.

These peep sights are to be used with a plumb line—one to hold the fixed end and the other as a guide hole in which a thread (black preferred) can be very nicely centered.

While the above method may appear complicated, it is really quite simple to carry out, and without having to work outside at night under poor light conditions, possibly annoyed by mosquitoes or with fingers numb with cold; risking the possibility of a series of observations being spoiled by clouds. We have accomplished indoors:

(1) Setting polar axis to our latitude
(2) Correcting any lack of perpendicularity between line of sight and declination axis
(3) Setting both circles correctly
(4) Setting our reference levels true.

When this has been accomplished, the mounting may be taken outdoors to pier or tripod, as the case may be, and leveled up ready for orienting to the meridian. If you know your longitude, which can most conveniently be read with all necessary accuracy from a U.S.G.S. quadrangle sheet, and your watch is adjusted by time radio signals, you are ready to select one of a number of equatorial stars and shoot it as many times as necessary in order to orient your outfit.

Theory: In the left hand drawing of Figure 3 the line PA represents the polar axis of the telescope as viewed from the "west," its angle of elevation being θ. The line AW, may likewise represent the optical axis when this is on the west side of the pier and pointing to the zenith or the nadir—that is, the optical axis is vertical.

If we now clamp the telescope in declination and revolve it about the polar axis through an angle of 180°, it is evident that point W will swing to E (now on the east side of the pier), and that to bring the optical axis again to the vertical without reversing the ends, we must sweep over the angle D.

From the construction of the drawing, the angle WAP is the complement of the angle θ, and from an early proposition in geometry angle PAW is equal to angle PAE.

Since our declination circle, even if not in adjustment, will give us the angle D, we have

$$D = 2(90° - \theta). \qquad (1)$$

Since our telescope is not yet in adjustment, angle θ is not yet equal to ϕ

(our declination), but we can say that $\theta = \phi + e$, the letter e representing the angular difference between the actual elevation of our polar axis and the elevation desired, which is our declination.

Substituting this value of θ in (1), we get

$$D = 180 - 2\phi - 2e, \text{ and}$$
$$e = 90 - \phi - D/2$$

The resultant sign of the value of "e" will indicate whether our assumption of the sign of "e" has been correct, or, in other words, this correction should be applied with its sign changed.

Theory: In the right hand drawing of Figure 3, shown in perspective, the polar axis PA is indicated as pointing out of the plane of the paper and inclined to our left at an angle of some 45°; its real value is unimportant.

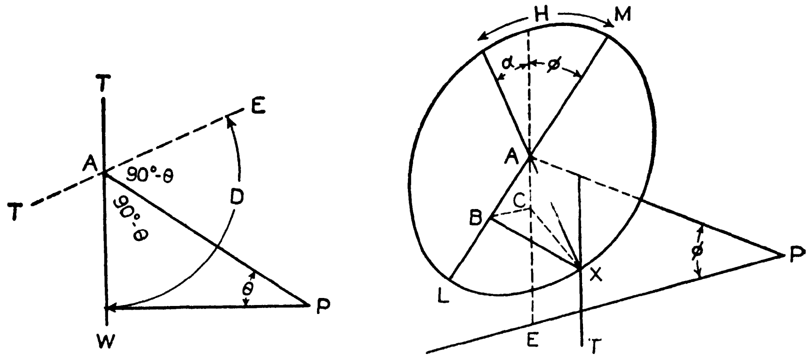


FIGURE 3

The ellipse represents the foreshortened circle which the declination axis R will describe if rotated on the polar axis about A as a center. The declination axis AX carries the optical axis XT at its outer extremity X. For our purpose, XT is supposed to be placed in a vertical position as indicated. This position is impossible at the angle shown, and is placed there only to facilitate the drawing and permit visualizing the construction triangle BCX. At the point where this relationship is applicable, namely, where the declination axis is nearly horizontal, this triangle nearly vanishes. Strictly, it can have no area except when the declination axis is slightly away from the horizontal and the optical axis vertical due to any deviation of the two from perpendicularity, and this is what we wish to investigate.

Draw the horizontal PE to lie in a vertical plane through PA, thus making the angle EPA the angle of elevation of the polar axis. This plane will also cut the circle described by the declination axis at some diameter LM. The line AE, perpendicular to PE, will then be vertical, and parallel to the optical axis XT.

Now, if through X we pass a horizontal plane, it will cut AL at B and

EA at *C*. The angle *ABX*, as well as *ACX* and *ACB*, will be right angles.

The angle *XAB*, which we have labeled *H*, will be given by the hour circle, and the angle *CAB*, marked ϕ, is evidently equal to the angle of elevation of the polar axis, while the angle α, between the declination and the optical axes, is to be determined in terms of the other two.

In the triangle *ACB*, $AC = AB \cos \phi$,
in the triangle *ACX*, $AC = R \cos \alpha$ and
in the triangle *XBA*, $AB = R \cos H$, and therefore

$$R \cos \alpha = R \cos H \cos \phi \text{ or}$$
$$\cos \alpha = \cos H \cos \phi$$

Example: What correction is necessary in the saddle, 9″ long, of an equatorial when upon reversal, the hour circle indicates a discrepancy of 30′ of arc, ϕ being 40° 56′.

Solution: Since reversal doubles the angle, the error on the hour circle is 15′:

$$\text{Cos } \alpha = \cos H \cos \phi$$
$$.00436 \times .74392 = .00324$$
$$\alpha = 90° \ 11' +$$

and $.00324 \times 9'' = .029''$, by which amount the saddle end, which was uppermost when tube was vertical, is too high.

Collimating a Cassegrainian. By Harold A. Lower, San Diego, California: When amateur telescope makers gather to discuss optical problems, one frequently hears the statement that "a Cassegrainian will not perform as well as a Newtonian." This is seldom disputed, but one does not often hear any explanation of the reasons for the supposed inferiority of the Cassegrainian.

With modern methods of testing, there is no reason for not making the optical surfaces good enough for good performance. Therefore it is suggested that the bad reputation of the Cass may be due to poor collimation, in many instances. In some cases, the maker may not realize that extreme accuracy of collimation is required, if a Cassegrainian is to perform well, and in other cases, he does not know how to obtain the necessary accuracy, even though he knows it is needed.

Good alinement is basically a matter of design, as it is almost impossible to obtain accurate collimation if the mountings of the optical parts are not firm, and yet capable of delicate adjustment. I have frequently seen telescopes which were well mounted, and with excellent optical surfaces, yet performance was not good because the prism mounting was shaky and easily jarred out of adjustment. Cassegrainians frequently suffer from this defect, and may also have a poorly adjusted secondary mirror which shimmies at the slightest jar. It is not surprising to find that the Cass has a bad reputation.

All the optical parts of any telescope should be firmly mounted, and screw adjustments should be provided for centering and squaring on. The secondary mirror, for example, should be supported by a stiff spider, capable of being accurately centered in the tube. The cell should be so mounted on the spider that it may be tilted in any direction for squaring on, and firmly

locked in position, when once adjusted. Figure 4 shows a type of secondary mounting which has given satisfactory results. With slight modification, this type of mounting can be used for a prism or diagonal.

Assuming that one has built a Cassegrainian, and has provided a rigid tube and firm mountings for the optical parts, the first step in alining the system is to adjust the eyepiece mounting. If the main mirror is not perforated, the eyepiece mounting must go on the side of the tube, and must point squarely at the prism or diagonal, which ever is used. To accomplish this, we first provide a section of tubing about a foot in length, which will fit the eyepiece mounting. This tube is fitted with cross-wires at one end, and at the other with a disk having a small hole in the center. Diametrically opposite the eyepiece opening in the telescope tube we place a target, which may be a chalk mark, or a small bit of white paper. This target is located

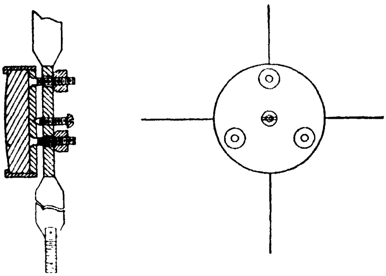


FIGURE 4

on the inside of the telescope tube, opposite the eyepiece opening, and its position should be determined by very careful measurement.

Having located the target, the next step is to slip the sighting tube into the eyepiece mounting and sight through it at the target. By means of shims or adjusting screws, the eyepiece mounting is adjusted until the cross-wires in the sighting tube are accurately centered on the target. This completes the adjustment of the eyepiece mounting, and if it has been carefully done, it will never need to be disturbed. If the main mirror is perforated, the adjustment of the eyepiece mount is a bit easier, as all that we need do is to stretch two strings across the front of the telescope tube so that they cross in the exact center. Then these strings become our target, the eyepiece mounting is centered, and adjusted until the cross-wires point at the two strings.

The second step is to place the spiders which will support secondary and prism (or diagonal) in position. These spiders should be adjusted by measuring, until the center screw hole in each spider disk is accurately centered in the telescope tube. Next, the prism is mounted on its spider and lined up by means of the adjusting screws until the cross-wires in the sighting tube point directly at the center of the prism and the reflection of the

central screw hole in the secondary spider disk is seen exactly centered by the cross-wires. An additional check on this adjustment is to sight through the center screw hole of the secondary spider. The image of the eyepiece tube should be seen in the prism, and the small hole at the eye end of the sighting tube should appear well centered in the prism. This completes the adjustment of the prism.

The third step is to place the secondary mirror in position. If the spider was carefully centered, the secondary should need only squaring on, which is done by means of the leveling screws. On looking through the sighting tube, one should see the secondary mirror, with the reflection of the prism and eyepiece tube well centered. If not, the secondary should be tilted until the image of the prism does appear centered, and the cross-wires in the sighting tube exactly cover their own reflection. A black ring, which is the reflection of the inside of the telescope tube, will be seen around the edge of the secondary mirror. This ring should appear of uniform width all around.

The fourth and last step is to place in position the main mirror. Assuming that the cell is centered with the tube, we will only need to square it up so that the mirror looks directly out of the tube. This can be determined with fair accuracy by sighting from the front end of the tube, past first one, and then another of the legs of the secondary spider. If the holes in the telescope tube for the legs of the secondary and prism spiders were carefully located, so that they are in line, we can square up the main mirror by adjusting it so that the legs of the secondary and prism spiders are directly in line with their reflections in the main mirror.

After adjusting the main mirror in this way, we remove the sighting tube, and look through the eyepiece mounting, and should see a number of concentric circles. These are the end of the telescope tube, the primary and secondary mirrors, and the eyepiece tube, and their reflections from the two mirrors. In the exact center, the reflection of the pupil of your eye should appear, and all of these circles should be concentric with it. If not, they can be made so by slight tilting of the main mirror. If the first adjustments have been carefully done, squaring on of the main mirror completes the job, but to be quite certain that every thing is right, the telescope should be pointed at a star and the eyepiece racked slightly in and out of focus. If collimation is correct, when the star is in the center of the field, the out-of-focus ring system should appear circular, and of uniform width all around. If it is elliptical, or the black spot is not well centered, there is an error. If the adjustments have been carefully made, alinement will probably be so nearly correct that it will require a fairly high power ocular to detect the error, but if the star test shows an error, very slight adjustment of the primary mirror should correct it.

This method of collimating a Cassegrainian may seem to be a lot of trouble, but it does not take long, and the improved performance will well repay the effort.

How to Make a Diagonal for a Newtonian

By JOHN H. HINDLE
Witton, Blackburn, Lancashire, England

Whilst the use of a totally reflecting prism on a Newtonian is permissible, we must use an optical plane of elliptical contour if we desire the very best results. Various methods, mostly unsound, of obtaining such a plane have been suggested; for example, cutting the ellipse from a piece of stout mirror glass, or by making a circular plane by well-known methods, and cutting the ellipse from that, etc.

It is almost impossible to pick up a piece of glass which is optically plane, and it is equally difficult to cut an ellipse from a good optical plane

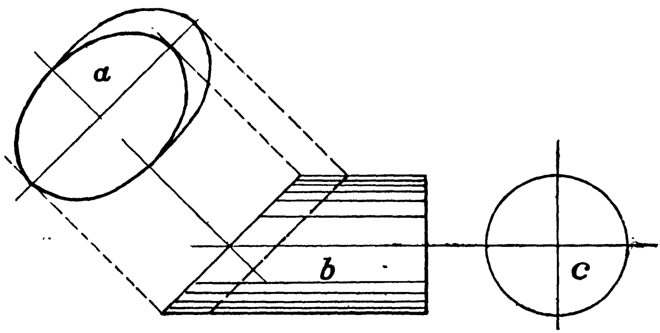


FIGURE 1

without serious deterioration of the optical surface. These two objections practically determine the methods by which a perfect optical plane of elliptical contour must be produced.

Such a plane (Figure 1 *a*) may be considered as a slice cut from the end of a glass cylinder (Figure 1 *b*) which has already been shaped at the end to an angle of 45°. The dotted line shows where the slice of glass would be cut off to give the required shape, which in one particular aspect presents a circle in elevation (Figure 1 *c*).

Several oval pieces of glass should be obtained, sufficiently large to allow for grinding down to the correct size. Note that more allowance is required on the major axis to include the thickness of the glass. This can be easily ascertained from a full size drawing.

We next require a short length of steel shaft (S, Figure 2, at left) about half to three quarters the finished minor axis of the ellipse in diameter. The end of this shaft is cut to an angle of 45°, and the piece of glass firmly attached with melted pitch. We place the shaft in the chuck (Figure 2, *c*). A flat-faced pulley *P*, say 6″ in diameter, is keyed on another shaft, also a vee pulley *V*, to take an endless rope or cord. This shaft is mounted on the

slide rest *SR* and the drive arranged from above, so that a forward movement of the rest does not affect the tension of the driving cord.

Neither a high speed for the lathe nor the grinding wheel is desirable; 20 r.p.m. for the lathe and 60 r.p.m. for the grinding wheel will be ample. Fine Carborundum is painted on to the wheel, using turpentine as a lubricant. A very slow feed, by occasionally tapping the handle of the screw with a wrench, is advisable. After each feed, allow time for the glass to be ground away by the abrasive. Too much haste will result in chipping of the glass, and possibly forcing it from its seat. When finished with a smooth edge, the beveled shaft is heated, and the perfectly shaped ellipse is detached and cleaned.

It now remains to put an optical face on one side. This can be done perfectly, only by providing a "surround" of similar glass. Assuming our

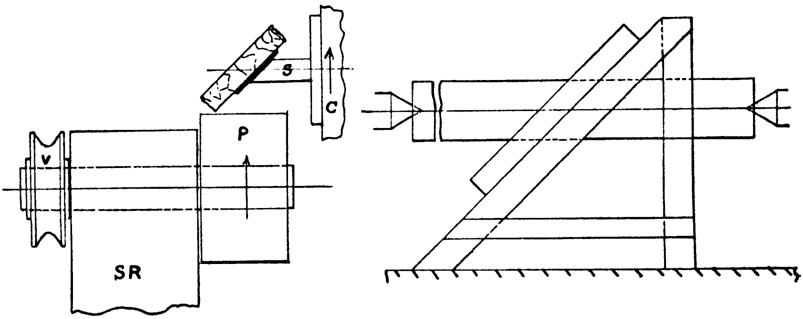


FIGURE 2

ellipse has a 1½″ minor axis, then we require a glass disk 6″ in diameter or thereabouts. This disk need not be edged, and it must be cut diametrically through the center. We now require to cut a piece out of each half, to accommodate the shaped flat between. The best method is to mount a 1⁹⁄₁₆″ or 1⅝″ shaft in the lathe (Figure 2, at right), and make a frame with a surface at an angle of 45°, permitting the two halves to be forced against the revolving shaft, to which Carbo and water is applied. We finally have three shaped pieces of glass which fit into each other perfectly (Figure 3, at left) when laid on a level surface. These three pieces are actually pitched on, in this position, to an iron plate, preferably of circular contour. When cold, melted beeswax is poured into the interstices, the surplus scraped off, and the surface rough and fine-ground to one level. The thickness of glass should be from one-sixth to one-fourth that of the minor axis. Sometimes there may be chipped edges which require grinding out, and a little extra thickness is a wise precaution.

Accuracy in fine-grinding is advisable, to avoid loss of time in figuring. The well-known method of using three disks, grinding each against the others in turn, may be adopted for getting the surface approximately flat. An-

other method is to fine-grind on the surface of a much larger piece of glass, which is known to be approximately flat. This leaves the surface of the composite disk slightly convex, which is always preferable, because it is easier to polish away a high center.

Before commencing to polish, scrape away the beeswax in the grooves just below the surface with the fingernail, and a smoother action of the polisher results. The polishing may be done either by hand, or on the drill press described in "A.T.M." If the iron plate is made of the section shown in Figure 3, center, and a similar section plate used for the polisher, a much heavier ring of iron, *I,* may be used to receive either, so that the polisher may be either above or below, alternately.

To test for flatness, we require a small spherical mirror about 6″ in diameter. The radius of curvature of this mirror requires consideration.

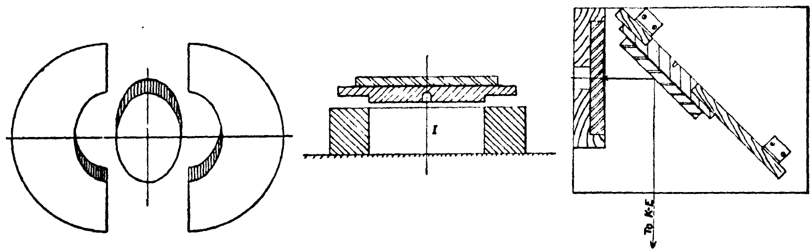


FIGURE 3

Theoretically, the longer the radius of curvature, the greater the accuracy obtainable. Practically, for a small flat, too great a distance prevents one seeing the surface of the flat intimately, and diffraction effects around the edge of the flat are somewhat confusing. 60″ radius of curvature is suitable for flats of 1½″ to 2″ minor axis.

A suitable arrangement for testing is shown in Figure 3, at right. The spherical mirror is mounted in a circular recess in a block of wood, which is screwed on to a flat board, edge-on to the observer. The composite mirror being tested is at an angle of 45° thereto. It is arranged in a vertical board having a hole of the required size, so that the complete arrangement can be rotated to the correct position, namely, when the major axis of the ellipse is horizontal, in which case the end view will be circular. It is then convenient to provide a close-fitting mask which hides the "surround." Alternatively, the surround may be painted with rouge and water, which quickly dries. The ellipse is approximately flat when the focus, in a vertical plane, coincides with that in a horizontal plane. To be more precise, find the focus moving the knife-edge horizontally, then withdraw the knife-edge just clear, and slide the blade of a pen-knife *up* the knife-edge. If the shadow comes *down* from the top the flat is convex, and vice-versa.

The test described should be used to *approximate* to a level surface. For

the greatest possible accuracy, we need a perfectly circular pinhole, and an ordinary eyepiece. We proceed to examine the image of the pinhole with the eyepiece, and expand the image on either side of the best focus. When the images expand identically on both sides of focus, the mirror is an accurate optical plane, and the clearest definition of the pinhole is obtained.

This method of testing is *extremely* sensitive, and in order to memorize it, the word HIVO has been concocted, that is to say, when the expanded

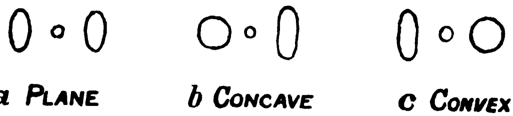


FIGURE 4

image is elongated "horizontally inside focus," and "vertically outside focus," the mirror is *convex*.

At this stage, it may be interesting to inquire whether this test can be used in making a *circular* optical plane. There is only one difference, the expanded images spread into an *elliptical* form, consequent upon the angle at which the plane is viewed. The figures *a, b, c,* Figure 4, show what might

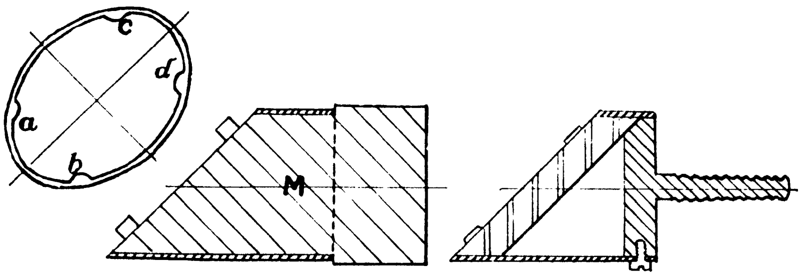


FIGURE 5

be obtained in the testing of a circular plane, when perfect, and when closely approaching perfection.

The pinhole image is shown in the center, the outside expanded image on the left, and the inside expanded image on the right.

Reverting to our original problem. Having now obtained our accurate optical plane, it can be removed from the iron plate and cleaned. The "surround" can be used again and again, with the aid of thin metal packings to raise them to their original thickness, if found necessary.

To mount the elliptical plane we require a short length of brass tubing, the interior diameter of which is a few thousandths greater than the minor axis of the mirror, a dimension which can be accurately obtained. This

tube is cut at an angle of 45°, in the manner indicated in Figure 5, at left, leaving four prongs, *a, b, c, d,* projecting, which are bent over to keep the plane from falling through. It is advisable to prepare a solid mandrel, *M,* with the end cut off at 45°, on which to bend over these prongs accurately;

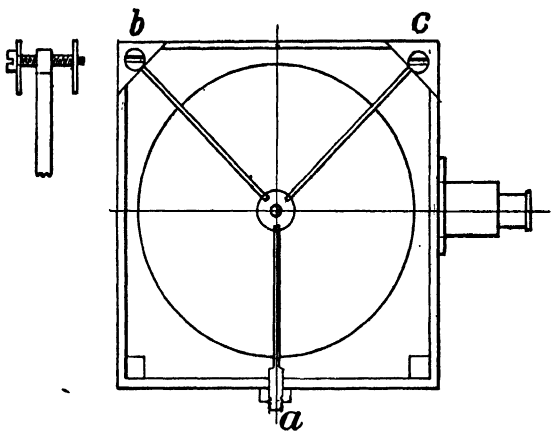


FIGURE 6

the brass tube should first be annealed by heating to a red heat, and plunging in cold water. After bending, the prongs can be reduced by filing to a minimum, safe, and symmetrical contour.

Finally, a brass disk to fit the tube, with a projecting screwed stud (Figure 5, at right) is fitted. A 45° bevel is filed on the inner edge in one spot, so that the plane mirror rests thereon. Three screws at 120° are used for fastening the disk in the tube, and the 45° bevel is carefully eased away with the file, until, with the three screws tightly home, there is just a perceptible "shake," ensuring that the plane is not nipped.

A cylindrical slip-on brass cover may be used to protect the silvered surface of the diagonal plane.

Figure 6 shows how the plane may be mounted in a square wooden tube. A three-armed support has a solid brass disk in the center, with a hole in which the flat is mounted. The lower arm *a* is fixed in a slot in an optimum position. The other two arms, *b* and *c,* are arranged so that they can be individually screwed either forward or backward. This adjustment, along with the possibility of revolving the plane itself on the optical axis of the cell, will give all the adjustment required.

Making Setting Circles—a Composite Chapter

[EDITOR'S NOTE: The chapter which follows is a collection of various amateurs' experiences—a sort of "testimonial meeting"—made up from descriptive letters received at various times and carefully saved up for presentation here. These informal letters reveal a variety of ingenious methods of getting around the lack of a machinist's dividing head, these being rather expensive. In addition to the methods which follow, the reader should

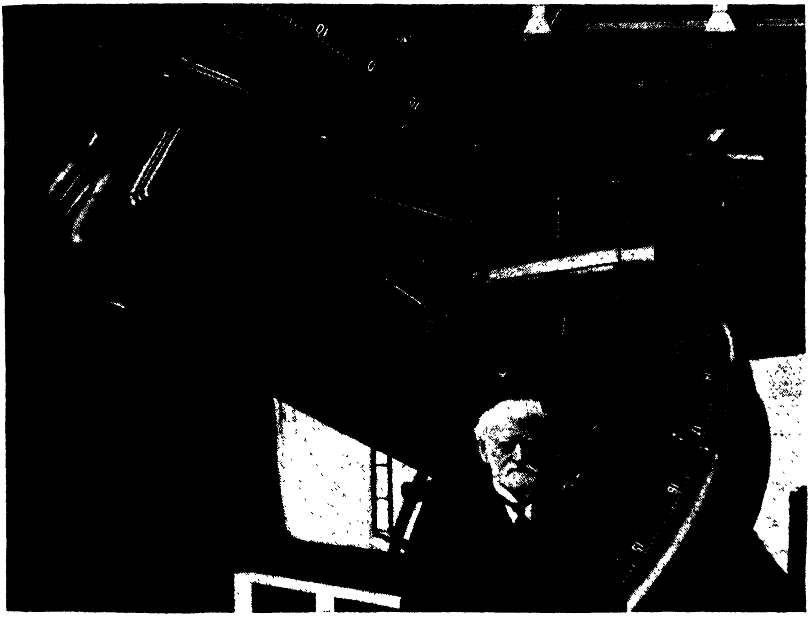


FIGURE 1

Circles on the 82" reflector of the McDonald Observatory, Texas, built by Warner and Swasey (showing Dr. Swasey). Even here the circles are not minutely divided. R.A. circle: coarse side, 12 subdivisions per hour; fine side, 5 finer divisions per subdivision (each 1 minute of time). Dec. circle: coarse side, divided into single degrees; fine side, each degree subdivided into six parts.

refer to the method described by Porter, in the chapter on design of mountings, also in the chapter on "Wrinkles," in "A.T.M."

Sometimes isolated workers are in doubt regarding the necessary closeness or fineness of subdivision which the setting circles of a telescope should be given, and wonder whether such coarse subdivisions as 360 intervals on the declination circle and 144 intervals (each one 2½°) on the R.A. circle

is fine enough for a good telescope. Others have endeavored to divide circles to a hairsplitting extent, but perhaps not thought to take equal pains in adjusting the telescope itself. However, such hairsplitting division is not usually indulged in on telescopes for the great observatories, since this is not regarded as necessary. Take, for example, the 23″ refractor at the Halsted Observatory at Princeton: O.G. by Clark, modern mounting (1935) by Fecker—a high-grade instrument. The declination circle is divided into single degrees, in groups of tens, sub-groups of fives, the R.A. circle into 5 minutes (time), in groups of twelves (equalling one hour), sub-groups of threes. The photograph (Figure 1) of the McDonald telescope tells the same story—simplicity, relative to the great size. In fact, there appears to be less tendency to complicate large professionals' telescopes than small amateur ones.

Prof. Heber D. Curtiss, Director of the Department of Astronomy at the University of Michigan, who is also a practical mechanic and designer, replied as follows, when asked about subdivisions on setting circles. "Finely divided circles are an anachronism, and an expensive one at that. We often used to say at Lick that we wished we had the thousand or so that must have gone into the fine circles on both axes. They are not even necessary. Those at Lick have been used twice—once when setting up the refractor, and the second time to test the orientation, etc., after an earthquake shifted the big affair bodily on its pier. I think I am safe in saying that no large telescope for the past few decades has been provided with accurately divided circles. The Crossley never had them in its remounted form. Large circles with easily read large divisions are the only thing nowadays. I have made no provision for fine circles at all on the design of our proposed large reflector."]

Harold Bakker, Berkeley, Calif.: The graduation of disks is a job. I scratched a circle, divided it into four parts with dividers, then divided these four parts into degrees by means of dividers. I used a jeweler's eyeglass, so that I could get accuracy. I have noticed that protractors, even fairly expensive ones, are not to be trusted. Some of the cheap ones are "off" as much as a degree. Polar coordinate paper is fairly accurate, and would save much trouble in making divisions. In all of these methods we are not sure, however, that we will get the graduations concentric with the axis.

Later I acquired a woodworking lathe which has a graduated head. Sixty holes are drilled in one of the pulleys, and a pin fits into these holes. The pin fits tight and there is no lost motion. By means of a very crude trial I found that this head is fairly accurately graduated, easily within a tenth of a degree. With this I clamp the circle in a four-jaw chuck, and place a sharp tool steel scratch pin in the compound. By means of this set-up I can easily, and with enough accuracy for most any amateur's telescope, put on my graduations. The lathe is an 11″ Delta.

Fred F. Flanders, Purchase Laboratory, State House, Boston, Mass.: I bought two, 3½″ brass disks, ⅛″ thick, from a local hardware firm. They have disks up to about 6″ diameter, and ¼″ thickness.

I first found the center and marked it with a light punch mark, by means of a sharp center punch. Then I marked a circle about ¼″ from the edge, by means of a pair of sharp dividers. Then I set off 6 points on this circle, by using the diameter. After checking carefully, I marked these points with a very light, sharp-pointed punch mark. I worked under a 3″ reading glass held in a clamp, and used a center punch made from the tail end of a small file, set in ¼″ brass rod for a handle, and ground to a fine point.

Then I used a small pair of screw set dividers and spaced each segment into 6 blocks. These blocks I divided into 4 divisions by the same method. This of course gives me only 2½° as my smallest division.

Having the main points punch marked and the others scratched, I drilled

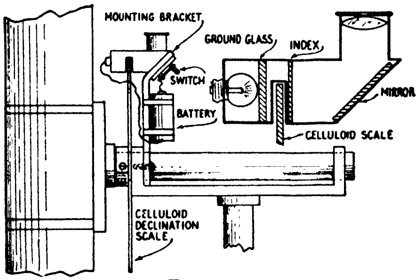


FIGURE 2

out the center of the disk, mounted it on a saw arbor and set it up in a small polishing lathe. By setting a small tool-rest tightly up against the disk, and working under a reading glass, a fairly good job of scratching the division marks was done with a scriber.

Dr. S. H. Sheib, Box 707, Richmond, Va.: I got a big panel of ply-wood and made a half-circle with a 30″ radius, and divided it up into single degrees, then drilled a hole at center and fastened a radial strip to it. I lay my metal plate at the center and lay off the degrees with far better accuracy than if I had tried to rule it direct. The long radius minimizes errors. (A superior method of squeezing down the errors—even better than laying off the circle on the direct basis of its own periphery. In contrast, note another method, sometimes used but bad, in which the protractor lies *within* the periphery of the circle which is to be scribed—magnifying the errors.—*Ed.*)

John M. Pierce, Springfield, Vt.: Graduations should be numbered on the hour circle in such a way that, as the telescope points farther and farther west, the index will read earlier and earlier time. (The actual direction on the telescope, whatever the type of mounting, will depend on how the circle is placed on it, whether the circle or the index moves, etc.). Unless the circle is graduated with corresponding accuracy, a vernier will be useless and a fairly coarse graduation, combined with interpolation by the eye, will prove more accurate. Great accuracy in circles is useless unless super-accuracy of

the mounting is attained. It is much easier to make a good circle than to place the axes of the telescope parallel to the earth's axis and at a 90° angle with one another.

Cyril G. Wates, Edmonton, Alberta, Canada: The scale proper is a disk of $\frac{1}{16}''$ Celluloid, one side of which is sprayed with black Duco. The scale divisions are cut through the Duco with a sharp knife, and the numerals scratched with a scriber. Work with a light under the Celluloid. This method gives very fine markings.

The scale is attached to a collar which clamps to the declination axis by a set-screw. The drawings (Figure 2), shows the common German type of mounting, but the same principle could be adapted to any mounting. The lens is a ten-cent magnifier. The mirror may be thin glass, silvered on

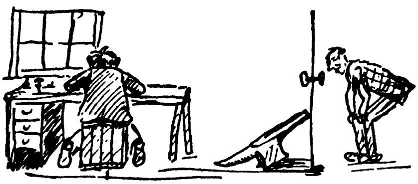


FIGURE 3

the front and lacquered. I used a bit of chromium plated metal. The "index" is a piece of Celluloid with a vertical line scribed and blackened. It should be as close to the scale as possible, in order to avoid parallax. Note that the Duco side of the scale must be next to the lamp, and that the base of the numerals must be toward the edge, as the mirror inverts.

The lamp is a 3-volt flashlight globe working on one cell, to give a faint light. The socket and one side of the switch are "grounded" on the mounting. This scale is delightful to use. The divisions are seen very clearly, yet the eye is not dazzled as when using a flashlight.

E. N. Ryder, D.D.S., Croton Falls, N. Y.: I obtained from one of the manufacturers of gears an iron spur gear of 9" pitch diameter, having 180 teeth, for about $3, and mounted this horizontally on a stand or table, so that it would rotate on a vertical stub shaft. On top of the gear I attached a circular wooden table to hold the annular flat ring of sheet metal which was to be marked. Above this, on a separate support, I mounted the marking tool, which was made from an old file ground to a point. This ran in a guide, in order to obtain marks of the desired length. The guide was provided with toothed steps, in order to permit making marks of different lengths. To rotate the gear accurately I dug out of a junk pile an old screw which served (well enough) as a worm * and, by rotating this worm through any desired part of a circle the trick was turned. (Dr. Ryder enclosed a pen sketch (Figure 3) with the statement that, when graduating

* Presumably a worm used for laying out setting circles ought to be termed an angleworm.—Ed.

circles, stern measures must be taken to exclude the garrulous, since close concentration is required.—*Ed.*).

Leo J. Scanlon and S. S. Weisiger, Jr., Valley View Observatory, Pittsburgh, Pennsylvania: Faced with the problem of making a pair of setting circles for a 12″ Springfield-type telescope, with a fair degree of accuracy,

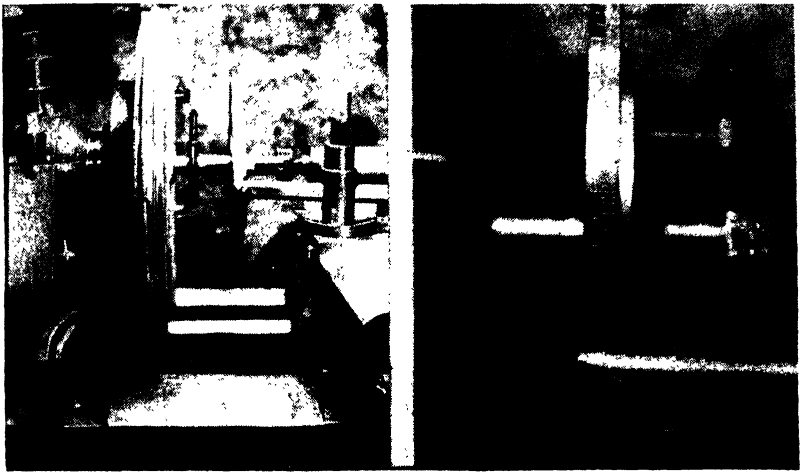


FIGURE 4

As described by Mr. Scanlon: "The photograph at the left shows, left to right; the headstock of the lathe we are using (20″ swing—though a 9″ swing could be used with smaller wooden disk and using the 1/16″ graduations on the tape for degrees) with a face plate attached. The wooden disk has been turned down after bolting to this face plate, so that when the flexible steel tape is wound round the disk, the zero and 45″ marks coincide. If one used a 9″ swing lathe (size usually in the shop of an amateur) he could have used about a 7″ wooden disk, and a 22½″ length of steel tape, each 1/16″ mark of which would correspond to one degree.

The disk to be graduated, in the right-hand photograph, is held firmly on the mandrel between centers in the lathe, and is made to turn without lost motion by means of a lathe dog embedded in a hole in the wooden disk or by other means. We bolted the circle to be graduated to a welded plate attached to the mandrel. The C-clamps shown in the left-hand picture, one at front and one at rear of the lathe, hold down the piece of angle iron which acts as a lathe stop. It is between this stop and the traveling carriage of the lathe that the observer inserts the different sized pins which control the length of graduations. The pins in our case were ⅛″ and ¼″ drill rod. These pins are in the hands of the observer, who looks through the reading microscope."

but not having access to a dividing head or a master gear with which to lay out the divisions, it was decided to attempt the work in a 20″, swing lathe, making the dividing head ourselves. Accordingly we purchased a 6′ steel tape in a hardware store, and cut off a 45″ length which, divided into eighths, gave us 360 divisions equally spaced.

A disk of wood, roughly octagonal, 16″ across the corners, was screwed to the face plate of the lathe, and turned down until the 45″ tape just met around the circumference, whereupon several small holes were punched in the tape and it was fastened to the periphery of the wooden disk with wire and screws (Figure 4, at left). This gave us a large circle, divided into 360 parts (actually 720, as there were 1/16″ divisions on the scale) to use as our dividing head. As an index marker, we attached by means of a large C clamp, a 30-power microscope to the lathe bed, where it would not interfere

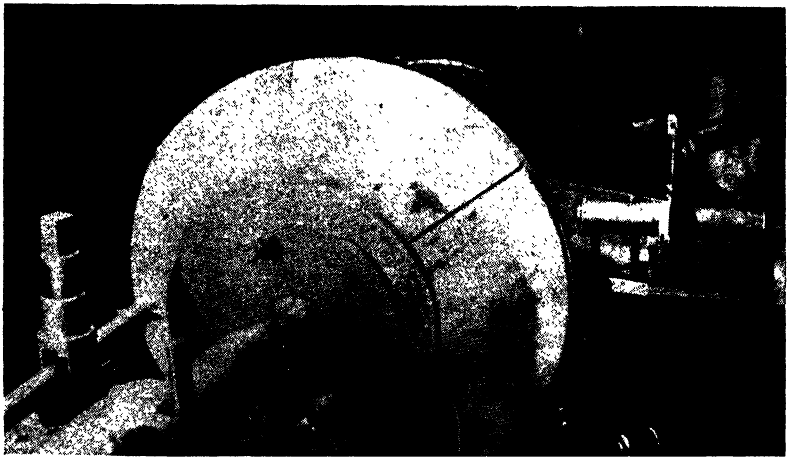


FIGURE 5

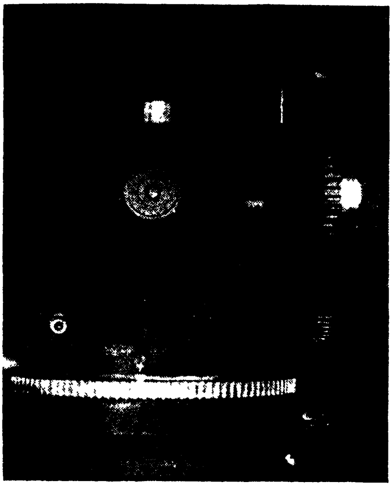
"This shows the circle being graduated. The traveling carriage of the lathe is moved by hand to make the engraving. It took about half an hour to do one circle. To the right is the reading microscope, in this case a ¾″ erecting eyepiece with cross-hairs installed. By pulling the belt, the whole mechanism is turned from one mark on the tape to the next. Account is kept aloud of the number of divisions, and the pin of correct diameter is inserted between the lathe carriage and the stop to control the length of the mark—long, medium or short."

with the working of the lathe and, on bringing one of the 1/8″ divisions to the cross-hairs, considered this part of the operation prepared for work (Figure 5).

The disk of steel, ½″ thick, to be graduated (Figure 4, at right) was placed between centers of the lathe on a mandrel, driven by a lathe dog inserted into a hole in the graduated disk. This provided an inflexible connection between the disk to be graduated, and our home-made dividing head.

The lathe was driven at ordinary speed long enough to take a light cut from the face of the work, in order to true it with the mandrel. The bearings on the headstock spindle were tightened to the point where it re-

quired a slight jerk of the driving belt to move the dividing head and the mandrel. An ordinary facing tool was ground narrow, so that about a $\frac{1}{32}''$ face was presented to the work. Since the first circle attempted was engraved on the top face of the R.A. gear, the cutting edge of the tool was located so that, when the cross slide handle of the lathe was turned in, the tool would make a radial cut on the gear face about 15 thousandths deep



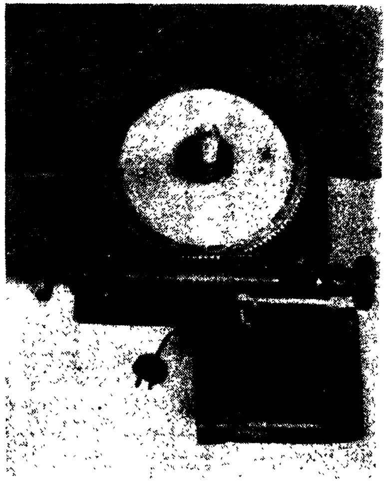


FIGURE 6

Circles made with the rig described. At the left is a Springfield type mounting made by Mr. Scanlon. Note the 'M.W.' type eyepiece barrel which rotates, permitting quick change from one eyepiece to the other. The base casting is made flat and is intended to fit on a pier that is sloped to the correct angle. The right-hand photograph shows the R.A. circle and motor drive.

and $\frac{3}{4}''$ long. This depth was adopted after several trial cuts, and maintained throughout all subsequent work.

In order to limit the travel of the cross slide, a stop was attached to the cross ways, at a point where the longest graduation would end. These were used every 15 divisions on the hour circle, and indicated hours. Every fifth and tenth division was about $\frac{1}{8}''$ shorter, while the degrees (or 4-minute divisions) were $\frac{1}{4}''$ shorter. To accomplish this, rods of steel stock were inserted between the stop and the cross slide, the thickness of the rod determining the length of the graduation on the circle face. These division stops were under the control of the observer, whose duty it was to look through the microscope, pull the driving belt by hand until the next index mark appeared in the field, and then count aloud the serial number of the graduation next to be made. In this way he kept a check on the number of

short and long divisions, and insertion of the proper thickness of stop in the cross slide of the lathe soon became automatic.

Once around the circle was sufficient, since the proper depth of cut was determined at the beginning. When the graduation was completed a light cut was taken off the face of the work, in order to remove burrs, and the numbers stamped on with dies secured at the ten-cent store. A jig was used to hold the circle and the dies, and a falling weight was used to secure uniform depth of figures. The weight, measuring $1\frac{1}{4}'' \times 2''$, was dropped each time through a $1\frac{1}{2}'' \times 15''$ guide tube supported directly above the die as it rested in the jig, but a space of 3″ was left between the bottom of the tube and top of the die when it was in position to receive the blow. Thus, when the weight, after falling through the tube and traversing this

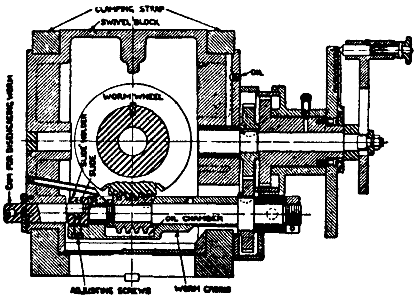


FIGURE 7

open space, struck the die and rebounded, it always fell back to one side or another, instead of again striking the die. Hence the blows were all equal. To hold the die a stick of wood was attached radially to the center of the circle, and its base and a vertical hole (jig) was bored at its outer end. This permitted swinging the die to each new position, also placing it accurately where the number was wanted.

When the edge of the declination circle (Figure 6, left-hand photo) was graduated, the same set-up was used. Instead of attaching a stop to the cross-slide, however, it was placed on the ways of the lathe, and the entire carriage mòved by means of the large wheel handle intended for that purpose. We found the work so interesting, and the results so highly gratifying, that several amateurs were invited to watch progress on the second circle to be graduated. This time, however, through lack of concentration, an extra mark was inserted where it was not required, and the error was not discovered until the graduation was almost complete. Then to our chagrin, we found that there was room for only three marks, where theory demanded four. Nothing to do but turn off all the marks so patiently made, and begin anew. This work is a one-man (or at best two-man) job; the presence of others is distracting, and inevitably leads to error.

With the method above outlined, we found it possible to graduate to

half degrees, but doubted whether in practice this was worth the effort. After the disks were numbered, we had them chrome plated for weather-resistance.

[Editor's Note: The method next to be described involves home-making a simple, inexpensive dividing head, hence, before going on, a word about the working principle of dividing heads in general may be pertinent.

In machine shops dividing heads are used as attachments to milling machines for all sorts of fancy purposes. Figure 7, reproduced by courtesy

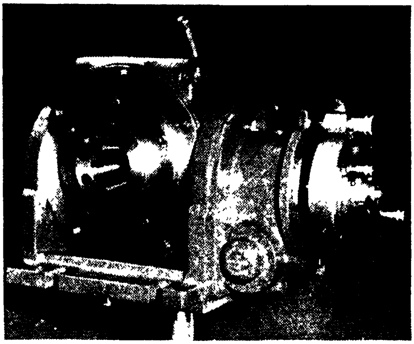


Figure 8

of the Cincinnati Milling Machine Company, shows how these work. The handle at the right has a spring pin that drops into holes evenly spaced around a circular index plate. Through the gears shown in section it actuates a worm and worm wheel, the work being attached to the shaft of the latter. Such rigs cost well up into the hundreds of dollars.

Figure 8 shows a dividing head plus a divider that divides to one second of arc, and is made by Kearney and Trecker. The cost is about the same as that of a medium-priced motor car. Most amateurs are lucky even to get a look at one, like a cat and a king.

In addition to these and similar dividing heads—simpler ones can be had for considerably less money but even then not cheap—there are some really ritzy ones called dividing engines which it is worth while at least to know about, even if they are quite beyond the moon. The one shown in Figure 9, in both front and rear view, was made by an amateur telescope maker, Vard B. Wallace of the Vard Laboratories, Pasadena, California—though he built it mainly for another purpose, the commercial production of protractors. He describes it thus:

"The table of the engine is a little more than 14″ in diameter and has 360 teeth cut on the edge. The table is split through the center line of the teeth, so that the upper half may be rotated with respect to the lower half. After the teeth were hobbed (in the Astrophysics shop at 'Cal Tech') the two halves of the gear were shifted and lapped 144 times in different positions.

The ultimate result was that there is no visible error in the teeth in any position when viewed through a glass.

At the left-hand side of the right-hand picture you will note a pair of cams on the same shaft as the crank. These cams actuate two pistons in small hydraulic cylinders. The liquid from these two cylinders flows through the tubes to the tracelet mechanism. One tube connects with a cylinder that moves the tracelet back and forth. The other raises the tool on the back stroke so that it is free of the table while the latter is turning. This will seem like a needlessly elaborate device till you consider that it is necessary to shift the whole tracelet mechanism laterally on the bridge to accommodate large or small protractors. It is required that the tracelet be raised and

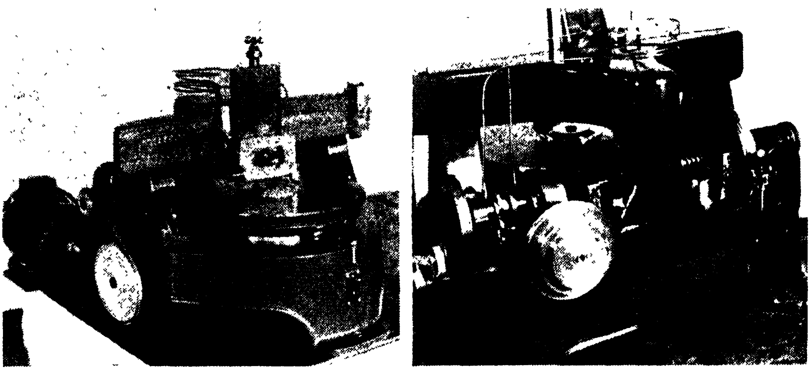


FIGURE 9

lowered to take thick or thin work. On top of all that it is also necessary to be able to rotate the tracelet so that bevel or even cylindrical work may be done. With the hydraulic system, all this is accomplished with no difficulty other than the slight bending of the tubing. To do the same thing mechanically is quite a task.

"The machine is almost silent in operation. The engine will scratch 360 lines on a disk in about 14 minutes, putting long and short lines in their proper places, and upon completing the disk it will shut itself off and ring a buzzer for attention. You will notice that the tracelet is inclined at a slight angle in the pictures. This was for some bevel work that we do in production."

The Vard apparatus, just described, is of course very far too fine an instrument to construct just to make circles for a telescope or two—in fact it is a much finer instrument than most telescopes themselves, and then some. The one in Figure 10 goes still further, being the circular dividing engine at the National Bureau of Standards and about the last word in such things. It can be used to graduate circles up to a meter in diameter. Such a machine costs about $10,000 or more, and will graduate so that the errors

are only about one second of arc and in some cases even less. This is better than a millionth of a circle.

Having made these flights into the empyrean, we return to earth at the lowly level of the average amateur, who seldom can find 10,000 cents, not to speak of $10,000, for a circle divider—in fact, 10,000 mills is about as much

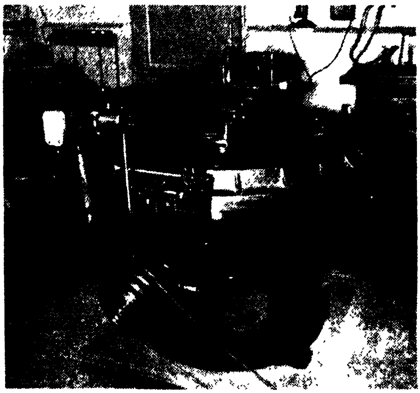


FIGURE 10

as he will be likely to want to lay out. The fun he has in planning, building and watching his "patent dingbat" work will repay that much outlay. The letters which follow show how two amateurs made dividing heads that were—well, good enough. There must be numerous other ways of doing the same thing—one, in fact, for each amateur who does it.

One simple way, if the telescope is provided with a drive having suitable gearing—that is, commensurate with the desired subdivisions on the circles—is to make use of it as a dividing head. A. W. Everest thus divided his circles on the telescope itself.]

Victor E. Maier, Indianapolis, Ind.: The parts of this machine (Figure 11) for marking setting circles consist of a home-made dividing head, a train of gears, a chuck to hold the work and the marking tool. The dividing head or index plate is of aluminum and is drilled to match the gear train, in such a manner that each hole in the plate moves the circle 30″ of arc. A counting arrangement rings a bell every fifth mark, which tells the operator the circle has moved 2½° and needs a longer mark. An inner circle of holes on the index plate is for use in laying out R.A. circles. The slide, equipped with adjustable bumpers for controlling the length of the marks, carries a sharply ground turning tool, driven by the long lever in the foreground. The slide carriage was the guide from an ancient shaper. The machine was built by Samuel S. Waters, president of the Indianapolis Amateur Astronomical Association.

J. W. Johnson, Chadron, Nebraska: Herewith is a sketch of a little device which I have found helpful. Any graduations desired can be had, by suitable choice of gear and dial divisions.

This is essentially a device for turning the setting circles through small, known angles while the marks are scribed by a tool held in the tool post. The tool carriage is moved by hand, if graduating the edge of the circle, or the cross feed run in and out if the marks are made on the face of the circle. The headstock does not revolve and should be blocked to prevent accidental movement.

The material needed is cold rolled steel or scrap iron. Although bronze

FIGURE 11

for the worm, and for washers between rubbing surfaces, would probably make for smoother operation, this is not necessary and the maker is most likely to use whatever comes to hand.

The contrivance consists of (1, see Figure 12) an axle with one end tapered to fit the head-stock spindle, and on which turns (2) a bushing which is a snug fit in the hole of the change gears supplied with the lathe, and having threads on the right end to fit the chuck and threaded for a collar on the left end. The collar clamps the gear tightly against the back of the chuck. A worm (3) whose bearing is clamped by a bolt to the face plate slot, at the proper angle and position to engage the teeth of the gear on the pitch circle. A weight on the end of the worm will keep it tightly engaged. (4) A dial which is divided as desired and is held on the worm by a pair of nuts. (5) A screw and washer in the end of the axle, to retain the chuck and gear.

Using a 36-tooth gear, the work will turn 10° for each revolution of the dial. Ten divisions on the dial will give graduation to 1°. Odd graduations for hour circles, verniers, etc., can be had by suitable choice of gears and a paper dial face divided as required and pasted on the dial.

In practice the circle is held in the chuck by bolting it to a block of steel or on an extra face plate, and turned true and polished. The chuck is then replaced by the face plate and the worm and gear assembled. The chuck is run on, and a pointed piece of metal clamped to the lathe bed for an index.

It is important to see that the slack is not allowed to alternate, but is kept in one direction for all marks. For the same reason, the different parts should fit as closely as possible, as the effects of lost motion will be readily obvious.

The tool should have its point on center. It has a shape similar to a threading tool, and is turned horizontally to cut when pushed. It is found that better marks are had if, with the tool in this position it is *pulled* across

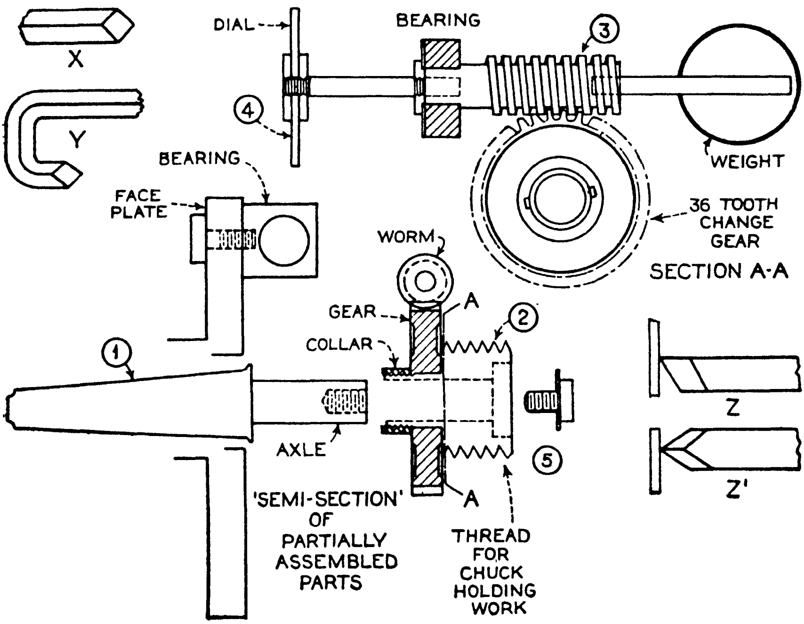


FIGURE 12

Details of the Johnson machine, as drawn by J. F. Odenbach from rough sketches in the maker's descriptive letter.

the work. That is, with negative clearance. I had planned to use a diamond point push tool, *X*, something like an engraver's burin, and tried it. It digs in and makes too deep a mark. Also, as it dulls, the cuts are not smooth. The next thought was a hook tool, *Y* of the same style, to pull. But this must be forged, and my blacksmith friend was getting a harassed expression,

so I postponed that. The tool actually used was similar to a threading tool but reversed and was pulled, Z and Z'.

The carriage is loosened so as to move freely and a few minutes' practice shows the right pressure to give the required depth of mark. The negative clearance of the tool prevents any tendency to dig in and make a rough mark. The slight burrs can be removed by *fine* emery paper while the circle is on the lathe. However, the marks will hold black grease (for visibility) better if not smoothed."

[EDITOR'S NOTE: After the preceding description had been prepared and sent in, and the drawings made, the owner became dissatisfied with the

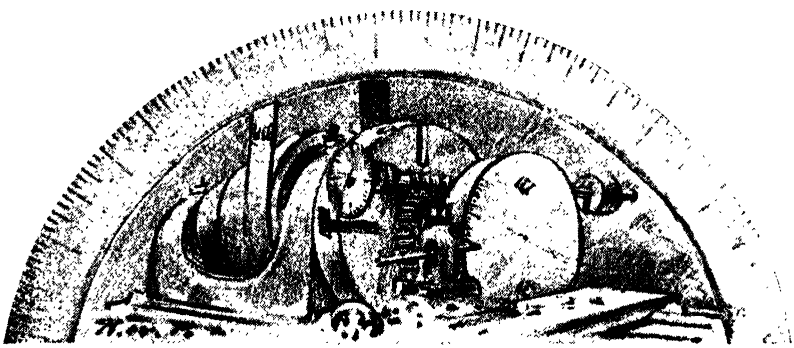


FIGURE 13

An interpretation of Johnson's drawing, done by Russell W. Porter. It was based on the first or spur gear attempt. Surrounding the drawing, for convenience in reproduction, is a rubbing made direct from the circle made when using the spur gear. A close study of the spacings reveals quite large, though non-cumulative, errors.

equipment because the divisions on the circles produced showed periodic inequalities—see the first rubbing, the one which surrounds a sketch of the rig (Figure 13). These inequalities were ascribed to the use of a spur gear instead of a worm gear, working in connection with the worm, and a change to a worm gear was accordingly made with the result shown in Figure 14. There errors are no longer noticeable, and probably come within the tolerance permitted of circles for most telescopes—something of the order of size comparable with the width of field of the eyepiece, assuming in the first place that the telescope is in good adjustment. Instead, however, of changing the description and drawings, the writer decided to present them "as is," since there is often a definite value in knowing certain things not to do. Otherwise, without mention of the experience of the maker of the outfit described—that is, going at first up the wrong alley—other amateurs might waste initial effort trying the same thing.

To his previous descriptions, Mr. Johnson accordingly has added the codicil which follows.]

A bronze worm-gear—40 teeth, 16 pitch—was bought at $1.50 and with it a hardened and polished worm, same price, from the Chicago Gear Works. The support for the worm was changed from the face plate to the lathe bed, the two bearings giving added rigidity and the face plate being released for holding the work.

When working on the setting circle, turn the dial so that the work revolves in the same direction it would in the lathe. The other way will give crooked marks if any play is present between work and worm. Be sure the chuck or face plate is set up hard against the gear. A slight movement here and the marks will fail to match when finishing out the circle.

I was able to put the graduations on both setting circles in $3\frac{1}{2}$ hours, with time out for many smokes.

The dials themselves were graduated without measuring anything, by a method that seems like hoisting one's self by one's own bootstraps. Having the worm gear, and assuming its accuracy, the next requirement is the division of the dials for getting fractions of a revolution of the worm. These could be divided by any of the methods suggested for dividing telescope circles,

FIGURE 14

A section of another rubbing made from a circle inscribed after a worm gear was substituted for the spur gear. The spacings are now uniform.

but I used the indexing head to graduate its own dials. I bolted several pieces of 16-gage iron to the face plate, and turned them round and drilled the central hole. One of these blanks was then put on the axle of the worm to serve as a dial. Another was put on the face plate and centered, to be divided into tenths. A single file mark on the dial blank indicated full revolutions. Every fourth revolution of the worm I made a mark on the edge of the blank on the face plate. Thus, in about 10 minutes, I had a blank accurately divided into 10 parts—no measuring, no protractor, no nothing. I then took off the blank dial and substituted for it the tenths one. Now 4 marks on the new dial equals .4 revolution of the worm and $\frac{1}{100}$ revolution of the work. So we divide a new dial into 100 parts. The $\frac{1}{100}$ dial can be used to make dials for any sort of graduations, by just a little arithmetic.

Most of us will want single degrees of arc and 5-minute (time) graduations on the respective circles. For this we want a dial divided into nine parts, with these quartered or $\frac{1}{36}$ least count. The following table gives total revolutions of the $\frac{1}{100}$ dial:

1/100 Dial		Work
0.		0.
1.111	rev.	1/36 or 10°
2.222	"	1/18 or 20°
3.333	"	1/12 or 30°
4.444	"	1/9 or 40°
5.555	"	5/36 or 50°
6.666	"	1/6 or 60°
7.777	"	7/36 or 70°
8.888	"	2/9 or 80°
9.999	(10 rev.)	1/4 or 90°

Then repeat.

Using this as a dial we can graduate in full degrees by turning it 1/9, or we can get five minutes of time by turning it 5/36.—*507 Mears Street.*

Telescope Drives

By Harold A. Lower
San Diego, California

The problem of driving an equatorially mounted telescope so that it will follow the stars accurately may be solved in a great many different ways. Practically every type of time-keeping mechanism that was ever invented has at some time been used for this purpose. To decide which kind of drive is best suited to any particular telescope, requires a knowledge of the use to which the telescope is adapted, as well as the degree of accuracy which is needed.

It seems to be the common impression that if we drive an equatorially mounted telescope at exactly the sidereal rate, it will follow the stars perfectly. Actually, this is only approximately true. Refraction shifts the position of the stars by an amount that varies with the zenith distance. This shift in the apparent position of a star affects both the right ascension and the declination. The shift in right ascension can be compensated by varying the clock rate, while the change in declination can be partly corrected by adjustment of the polar axis. For a telescope which is used only for visual work, the effect of refraction is not great enough to be troublesome if the instrument is driven at the sidereal rate. It could also be used for photography, provided the exposures were fairly short.

If we assume that the polar axis of the telescope is adjusted parallel to the axis of the earth, the clock rate which will be required to follow an equatorial star at the meridian is slower than the sidereal rate by 1 second per hour, or 24 seconds per day. At various hour angles east or west of the meridian, the clock must be slower than the sidereal rate by the following amounts.

Hour angle	0	1	2	3	4
Losing rate	1.0s	1.1s	1.3s	2.0s	4.0s

The adjustment of the polar axis has some effect on the clock rate, as well as on the shift of a star in declination. By adjusting the polar axis so that it points, not to the true celestial pole, but to the apparent pole, as lifted by refraction, we simplify the problem. By so adjusting our instrument, the effect of refraction on the declination is neutralized in a complete circle around the sky at the altitude of the pole. The clock rate at the zenith becomes sidereal. The following of the instrument for stars on the meridian will be accurate, and the clock rate suited to correct in right ascension at the altitude of the pole will be constant for stars in any part of the sky, at that altitude. Therefore it is good practice to adjust the polar axis to the refracted pole, and to rate the clock to lose about 24 seconds per day on sidereal time. The additional changes needed to follow a star accurately in any part of the sky can best be made by careful hand guiding.

To adjust the polar axis so that it points to the refracted pole is not difficult, but it can best be done by photographic methods. First, the tele-

scope is adjusted by the usual visual tests until it will follow the stars with fair accuracy, then the clock is rated on an equatorial star which is near the meridian. If our telescope will cover a wide enough field, we can use the telescope as a camera in the following test. If not, we can mount a fairly long focus camera parallel to the telescope, and use it instead.

Point the telescope to the pole, with the instrument set at hour angle 0 hrs., 0 m., with the telescope on the east side of the mounting. Focus on the pole star, and expose a plate for about 10 or 15 minutes, with the clock running. Then stop the clock, but continue the exposure for two or three minutes more.

Unless the polar axis points exactly to the refracted pole, the star images will trail slightly on the plate, even while the clock is running. The supplementary diurnal trails which are produced when the clock is stopped enable one to tell which way the star images were moving while the clock was running. After development, the plate is examined with the glass side next the eye, and held as it was in the camera, in relation to the horizon. When so examined, the direction of the trails which were produced while the clock was running will tell us which way the polar axis points with relation to the pole. The following rules are based on the direction the stars were trailing.

Trails point up	Axis points west of pole
Trails point down	Axis points east of pole
Trails point right	Axis points above pole
Trails point left	Axis points below pole

If the trails run diagonally, correction is required both in altitude and azimuth. After determining the direction of the error, we adjust the polar axis slightly, and expose another plate. If the adjustment was in the right direction, the trails will be shorter, and continuing the process with longer exposures will enable us to aline the polar axis to a high degree of accuracy.

Telescopes which are used mainly for visual work do not have to be alined with great accuracy, as an adjustment which is close enough to enable one to locate objects with the setting circles is usually all that is required. Also, the requirements as to accuracy of the clock drive are not severe. A clock which will follow at the sidereal rate is quite good enough, even for large instruments, and for small portable telescopes the clock may be quite crude and still give satisfactory results.

For photography the requirements are more severe, and it is well worth our while to make everything as accurate as our ability and bank roll will permit. Really excellent photographs of the stars have been made with very simple equipment, but it is probable that in most cases a good synchronous motor drive will be the cheapest and best for photography. Since most large power systems now regulate the frequency quite accurately, a gear train which will drive our telescope at the sidereal rate will enable us to use the telescope for visual work without any more bother than turning on the current. Guiding will enable us to make pictures, even with

long exposures, and while the sidereal rate is not exactly what we need, it is so near to it that the labor of guiding is not great.

Any outfit which is intended for photography must be rigid and free from vibration, as well as from any periodic errors such as may be caused by a drunken worm, or gears which do not mesh perfectly. Bevel or spur gears, if used, should not be located near the slow speed end of the drive, otherwise there may be a slight irregularity in the drive every time a tooth engages. We had one experience with this trouble. The main worm shaft of our telescope was driven by a pair of bevel gears, and while the drive seemed perfectly smooth by visual tests, we found that long-exposure photographs always showed stars slightly elongated. By some photographic detective work, the trouble was traced down to the bevel gears. An exposure was made on the Pleiades, with the clock rate set fast, so that the stars would trail. The exposure was timed during one revolution of the large bevel gear, and when the plate was developed, an examination with a pocket magnifier showed a series of knots, or condensations, in the trails, just equal in number to the teeth in the large bevel gear. This method of testing a drive will also reveal a defective worm, but if one uses only hard worms, with ground and polished threads, there is not likely to be any trouble from bad worms. Bevel gears, however, should be avoided, and worm or spiral gears used instead, if the very best results are required.

Periodic errors usually originate in the slow-speed end of the drive, and careful attention to seemingly unimportant details here may prevent trouble which is sometimes difficult to locate. The main worm shaft should be checked for straightness, and should be a tight fit in the worm; a loose fitting worm may become eccentric, due to the key forcing it to one side. Set-screw collars which take the end thrust of the worm shaft should also be tightly fitted, and the bearing faces checked, to be certain that they are at right angles to the shaft. Ball thrust bearings are advisable here, as no end play should be permitted in the main worm shaft. If guiding is accomplished by moving this shaft endwise by means of a screw, a heavy spring, working against the screw, should be employed to take up all slack in the screw threads.

The high speed end of the drive is not likely to cause any periodic errors, but friction should be reduced to the absolute minimum, particularly if using an electric clock motor. These motors develop very little power, and a small amount of friction in the high speed end of the drive may easily overload the motor. All rapidly moving parts should be checked to see that they turn very freely. Good lubrication is required, and if the gears are not enclosed in a case which can act as an oil reservoir, it will be necessary to use a light grease which will stay on the gears. After considerable experimenting, we found that a light graphite grease, thinned with about an equal quantity of oil, was satisfactory.

To prevent possible damage to the gear train, the final connection between the main worm wheel and the polar axis should be some form of friction clutch which can slip when the telescope is moved by hand. This

will also afford an opportunity for the right ascension dial to be made movable. Friction with the hub of the worm wheel will drive this dial at the sidereal rate, as long as the clock is running. When starting observation, this dial may be set by pointing the telescope to a navigation star and turning the dial by hand until the index reads the R.A. of that star. Once set, it becomes a sidereal circle, and any object can be found by setting to the proper declination, then turning the telescope until the index on the

FIGURE 1

Left: C. C. Chapman with his small telescope, driven by an alarm clock movement, assisted by a phonograph spring. Right: A close-up of the drive shown at the left. The phonograph spring lies behind the large gear on the polar axis shaft.

polar axis indicates the right ascension of the desired object. All calculation of hour angle has been eliminated.

Although mounting design perhaps has no place in this chapter, I think all clock drive builders should realize that no clock will perform properly unless the mounting is well balanced and moves freely. Ball bearings for the polar axis are needed, unless the drive has considerable power. If your telescope is large and heavy, and is equipped with plain bearings, a $1/20$ H.P. motor is a safer bet than one of the small electric clock motors.

For small portable telescopes, or instruments of moderate size which are located where electrice power is not available, an ordinary alarm clock may be used as a drive. As the alarm clock will not have power enough to drive the telescope, a phonograph spring is used for this purpose, and the clock merely regulates the speed. An excellent example of this inexpensive drive is shown in Figure 1. This was constructed by C. C. Chapman, 3715

Fairmount Blvd., Riverside, California. Mr. Chapman describes the drive as follows.

"The clock is a cheap alarm clock, with all the parts not used, (alarm gears, hands, case, etc.) discarded. I soldered the shaft upon which the minute hand was located, to the gear which drives this shaft. (The clock had a friction arrangement which allowed the clock to be set, and this needed to be made solid.) This shaft, with hour hand and gears which drove the hour hand removed, rotates once per hour, and thus needs to be reduced by 24 to 1 in order to drive the telescope one revolution in 24 hours. The clock can be speeded up enough to make it follow the stars, the

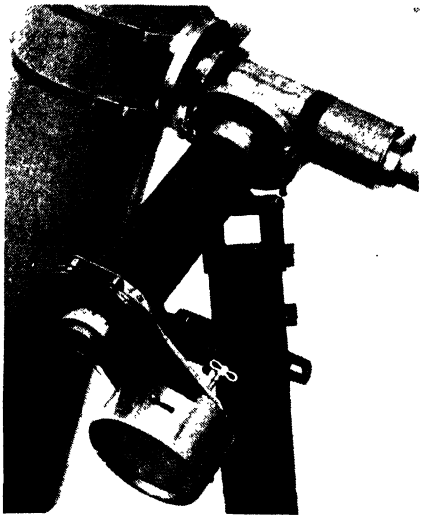


FIGURE 2

Mounting of Prescott's portable telescope (itself a good design—ample axes) with drive at the end of the polar axis shaft, showing the axes and alarm clock drive. As in the case of the drive shown in Figure 1, the alarm clock was not strong enough, and reinforcement in the shape of a stronger spring was provided. A similar case is described by von Arx, in his chapter on Stellar Photography—see his Figure 4.

regulator being adjusted to make the clock gain nearly 4 minutes per day.

"The 24-to-1 reduction is made in two steps. A 120-tooth gear on the polar axis of the telescope meshes with a 30-tooth gear. On the same shaft with the 30-tooth gear is a 96-tooth gear which meshes with a 16-tooth gear. The 16-tooth gear is connected to the shaft of the clock which rotates once per hour, through a universal joint which keeps the parts from binding, if not quite in line."

The largest telescope which I have seen with this type drive is an 8" portable Newtonian which was built by A. E. Johnson, of Riverside,

California. It is a very neat job, and the performance is all that could be desired. The 'scope follows the stars nicely, and no trace of vibration from the drive could be noticed.

Another alarm clock drive is that of Fred L. Prescott, 3111 Brooks Street, Dayton, Ohio, shown in Figure 2. Mr. Prescott describes it as follows: "The polar axis turns in a tube with suitable bushings, which in

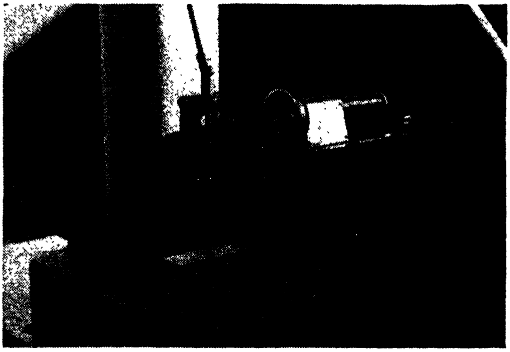


FIGURE 3

Byron L. Graves' Dictaphone drive—proof that a good drive can be made from parts picked up at the second hand store. It is mounted on rubber.

turn rotates in the polar axis housing. This tube has a 5″ drum at the lower end, over which a stranded wire cable (airplane control cable) passes, making 1½ complete turns. The clock, an old alarm clock, has the spring removed and a 1¼″ drum fitted, with the cable passing around it several turns and fastened to the drum. On the other side the cable winds up on a ⅞″ drum to which an 8-day spring is connected. The spring thus draws the cable in, turning the polar axis bearings in sidereal time, the clock escapement regulating the speed. The 4:1 ratio is just right, since the key of the clock makes four complete turns in 24 hours. The diameters given are 'pitch diameters'—to the center of the cable."

While the synchronous motor drive is probably the best when the frequency is accurately regulated, there are a number of other motors which may be used, and which, if the frequency regulation is very poor, might give better results than synchronous motors. An example of this is the drive constructed by Byron L. Graves, 1145 South Rimpan Street, Los Angeles, California. Mr. Graves used an old Dictaphone, with a governor controlled motor. A 288-tooth worm wheel on the polar axis, and a 5-to-1 bevel gear which drives the main worm, are the only gearing not shown in the illustration (Figure 3). The large bevel gear on the main worm shaft is clamped to the worm shaft by a nut which can be quickly loosened when it is desired to turn this shaft by hand, for adjustment in right ascension.

The bevel gear on the worm shaft, while not recommended for photography, is perfectly O.K. for visual work, and in this case, at least, does not produce any irregularity which can be noticed when using the telescope. Mr. Graves states that the governor is easily adjusted to make the telescope follow the stars, and that the drive has been entirely satisfactory.

Several amateurs have built somewhat similar drives, using disk type Victrola motors. Mr. Wm. S. von Arx, 573 Monroe St., Brooklyn, N. Y., has built a drive of this type and has used it for photography, with excellent results. He describes it as follows.

"It is an ordinary disk Victrola motor, with a seemingly inaccurate governor to keep it in step with the stars. This, revolving at about 30 r.p.m., drives by belt a box of various and sundry gears which reduces the speed to $1/10$ r.p.m., which in turn operates a worm ratio of 1 to 144, which is on the polar axis. You may question the belt's efficiency, but I have found it a handy thing because a little handle on the gear box pulley makes a fine adjustment in R.A. which can be manipulated without stopping the motor or permitting the slack in the gears to manifest itself. The adjustment is usually very slight, and the motor reengages the worm instantly, without any fuss with complicated clutches, etc., to be handled in the dark. Changes in temperature do affect the tension of the belt, and have sometimes allowed it to slip, but I have remedied this by a spring for constant tension, pulling the entire gear box against the belt. Thus far, I have had no trouble with this arrangement, and find that its sheer simplicity is a great aid in making quick and accurate adjustments in R.A.

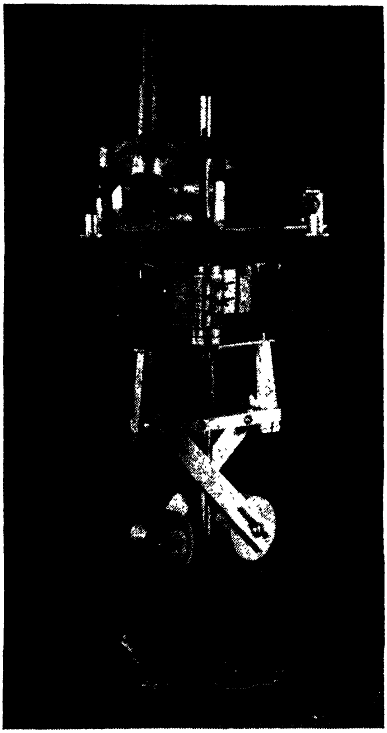
"The declination adjustment is a high ratio worm operating directly on the declination axis, but this is rather unnecessary, because there is seldom any correction needed in declination when the polar axis is well adjusted. The quick motion in R.A. is a matter of disengaging the main worm on the polar axis, reengaging it when the required R.A. is attained, and for fine adjustment, the pulley on the gear box is used. In declination, I have a plate clutch which releases at a certain torque. Simplicity itself, what?"

Mr. E. H. Morse, of 2401 Mar Vista Ave., Altadena, California, has devised a very ingenious motor drive which makes use of a slow speed universal motor which is controlled by a built-in governor. As this motor will operate on current from a 6-volt storage battery, or on alternating current stepped down to 6 volts by a toy transformer, it is suitable for a portable telescope or for a permanently mounted instrument. The performance of this drive is excellent, although it is not expensive to construct. But we will let Mr. Morse tell us about it.

"The telescope driving clock described as follows is similar to the one made by me and used on my 15″ reflector [see photo, "A.T.M.," p. 355—*Ed.*] for the past seven years. It is designed to run on current from an automobile, thus being useful to those owning portable instruments, although it works as well on house current transformed to 6 volts.

"Action of the drive is as follows: Current enters at lower bearing,

(Figure 4, right) travels to commutator and through one brush to the pair of magnets connected thereto. This causes the armature to rotate one-eighth turn, whereupon the current is cut off by the normal rotation of the com-



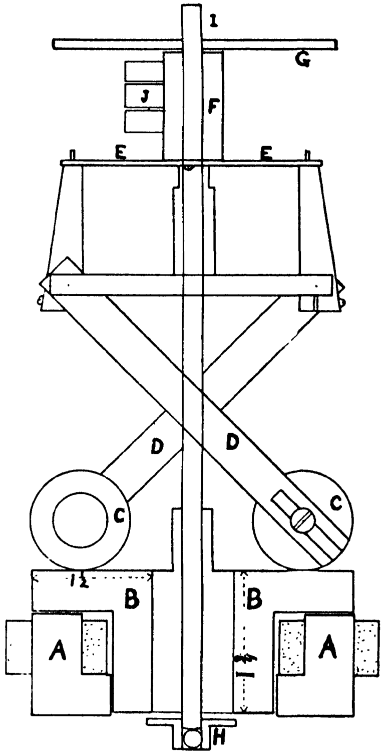


FIGURE 4

Left: A governor-controlled universal motor for telescope drive, built by E. H. Morse. Right: Diagram of the motor shown at the left. A,A, magnets. B,B, armature section. C,C, governor weights. D,D, governor arms. E,E, governor connecting links. F, commutator. G, rotatable brush carriage. H, lower bearing with ¼" steel ball, to take the thrust. I, upper bearing; this is plain. J, brushes—carbon.

mutator from that pair of magnets and conducted to the other pair through the other brush—and so on. When sufficient speed is attained to raise the governor weights, their movement causes the commutator to rotate forward slightly, cutting off the current sooner and decreasing the speed. A very slight rise of the governor weights causes sufficient rotation of the com-

mutator to give very close speed regulation. (I have kept a star on a knife-edge for a considerable time.)

"The photograph (Figure 4, left) shows the worm reduction gear attached directly to the clock, for purposes of illustration. This is incorrect. In order to kill vibration on light mountings, the reduction gear should be attached to the telescope mounting, the drive being from motor shaft to reduction gear shaft through a 'lathe dog,' the clock itself resting upon a cushion of sponge rubber.

"Commutator segments shown shaded (Figure 5) are grounded to the shaft; unshaded segments are insulated and carry no current.

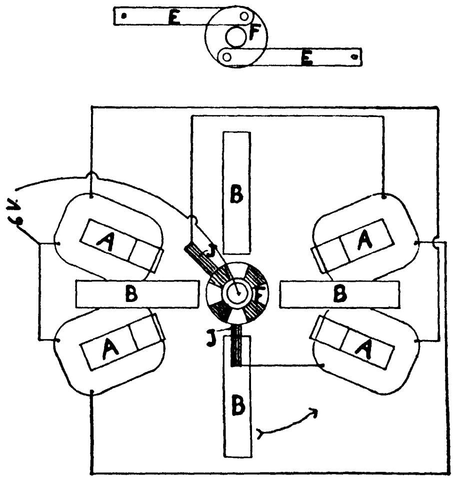


FIGURE 5

Plan and wiring diagram of the Morse drive. A,A, etc., magnets. B,B, armature sections. E,E, governor connecting links. F, commutator. J,J, brushes.

"Magnet and armature sections are cut from sheet iron with snips, varnished with shellac, insulated with paper between each layer and then baked, forming a solid piece.

"Base, top and pillars were made of wood; brass would be better.

"Armature sections are mounted in slots sawed in a wooden spool, as shown. They or the magnets must not be surrounded by an electrical conductor if you ever wish to use alternating current.

"Wire: Ten layers of No. 22 copper magnet wire, for 6 volts.

"Figure 5 shows the relative position of magnets, armature sections, commutator, brushes, and wiring diagram. It will be noted that the magnets are placed 45° apart, thus making four do the work of eight; also that they are so shaped as to utilize both poles very close to the armature sections.

"Figure 5 also shows how the commutator is rotated slightly by the rising of the governor weights, through the link action.

"Speed adjustment is obtained by increasing or decreasing the effective length of the governor arms; final adjustment by slight rotation of the brush carriage. Speed obtained with size shown in diagram is about 160 r.p.m.; with governor arms ½" shorter it is about 180 r.p.m. The one shown in the photograph runs 200 r.p.m.

"Speed is determined by a stroboscope disk lighted by a neon glow lamp. The number of spots on the stroboscope disk will depend upon the number of cycles per second of your circuit, and the speed desired.

"All rotating parts are fixed to the ¼" shaft by set screws, except the commutator, which is, of course, free to rotate."

Synchronous motor drives: Weight drives, controlled by a conical pendulum, have for many years been the usual method of driving telescopes in large observatories, but recently there has been a trend toward synchronous motor drive. This has been due to two factors. First, the difference in cost, which is much less for the motor drive. Secondly the accuracy of the synchronous motor drive, which has, in several cases where the conical pendulum drive was replaced by a motor, revealed periodic errors in the gear train which had not even been suspected, owing to the irregular control of the conical pendulum.

The accuracy of a synchronous motor drive, of course, depends on the accuracy with which the frequency is controlled. Therefore it would be advisable for any one intending to build one of these drives to investigate the accuracy of the local power supply. In most cases inquiry at the office of the power company will enable one to decide whether the control of the frequency is good enough for a drive of this kind.

The staff of the McMath Observatory and the Detroit Edison Co. have worked out a system of frequency control which is probably the most precise method of driving a telescope which has yet been developed. This system permits the astronomer to regulate the frequency of the power supply so as to vary the speed of the motor, thus adjusting the rate to compensate for the effect of refraction. The success of this system at the McMath Observatory has led to its adoption for the large McDonald telescope of the University of Texas. Unfortunately, this system of frequency control is quite elaborate, and would probably be much too costly for the average amateur. However, the frequency control of most of the large power systems is quite good, and in most cases would be as accurate as any conical pendulum drive which could be constructed by amateurs.

Since the introduction of electric clocks for use in the home, the frequency of most power systems has been regulated to give standard time. Now this complicates matters a bit, as we need sidereal time, or a close approximation to it, for our telescope drive.

Quite a number of different gear trains have been worked out which will enable one to use a synchronous motor, and still drive the telescope at about the sidereal rate. The selection of a suitable gear train is a matter

of individual preference. Some amateurs have hobbed out worm wheels by the use of a tap mounted between centers in a lathe. Others, who have access to a milling machine, can make gears to suit their own ideas. Most of us, however, will have to use the stock gears that are obtainable in quite a wide variety of sizes and ratios. The Boston Gear Works, North Quincy, Mass., and The Chicago Gear Works, 771 West Jackson Boulevard, Chicago, Ill., list 100-tooth worm wheels, which in suitable sizes are satisfactory for the main worm wheel on the polar axis. If one wants a main worm wheel with more teeth than this, the Lee Mfg. Co., 14269 Northlawn Ave., Detroit, Mich., can supply worm wheels of 359 and 360 teeth.

One of the easiest ways of making the change from standard to sidereal time is to introduce at some point in the gear train a pair of spur gears of 365 and 366 teeth. 48-pitch brass spur gears of 365 and 366 teeth can be obtained from either the Boston or Chicago gear works. As these are not regularly stocked, they will cost a bit more than regular stock gears of equal size. If several persons were to order together, a reduction in price could be obtained, the amount of the reduction depending on the number of gears ordered.

Calculating gear trains is by no means as difficult as some folks seem to believe. It does not require a mathematical genius and a slide rule. On the contrary, only the simplest arithmetic is needed.

As an example of how to do it, we will assume that we have a synchronous motor which operates at 2400 r.p.m., and that we intend to use a 100-to-1 worm gear on the polar axis. Looking through a list of stock gears, we find that we can get a 120-tooth, 48-pitch worm gear which will do nicely for the first reduction from the motor shaft. 2400 r.p.m. divided by 120 gives us 20 r.p.m. Now there are 1440 minutes in a day (standard time), so our main worm shaft will make one revolution in 14.4 minutes (1440 divided by 100). As we have reduced the motor speed to 20 r.p.m., we now multiply that by 14.4, which gives us 288. Looking through our gear catalog, we select a 72-tooth, 32-pitch worm wheel to turn our main worm shaft. 288 is now divided by 72, which gives us 4, and a 4-to-1 reduction is easily obtained by the use of two 48-pitch spur gears of 12 and 48 teeth, respectively.

We have now obtained a drive which will cause our telescope to make one revolution in one civil day, just like any electric clock. But we wish it to make one revolution in one sidereal day, so we add to our gear train two 48-pitch gears, of 365 and 366 teeth, which will speed up the rotation of our telescope by just about the right amount.

The resulting gear train would be arranged like this:

(2400 r.p.m. motor, worm) (120-tooth worm wheel, 12-tooth spur gear) (365-tooth spur gear, 366-tooth spur gear) (48-tooth spur gear, worm) (72-tooth worm wheel, worm) (100-tooth worm wheel, polar axis). Units in brackets operate on the same shaft, and mesh with next unit following.

This would give us a satisfactory drive if our power supply was 60 cycles, but if we happen to live in a locality where the power supply is

50-cycle, then we must use a 100-tooth worm gear for the first step in the reduction from the motor shaft, instead of the 120-tooth worm gear given in the example above, as our motor speed would be 2000 r.p.m. instead of 2400 r.p.m.

When designing a gear train, one should be careful to check the direction of rotation, as it is rather annoying to get a drive all assembled, and then find that the telescope turns the wrong way. Some synchronous motors are easily reversed, if this should happen, but some are designed to run only in one direction, so it is better to check rotation first. Spiral gears can

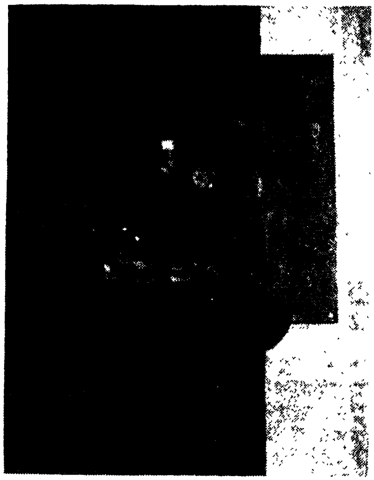


FIGURE 6

An example of the neat, compact design which is possible with an electric clock motor. Springfield type mounting, 12", built by Leo J. Scanlon. The motor is a 2400 r.p.m., synchronous, with two reduction units—all housed in a metal box 3½" × 6" × 6", including a fan for cooling. The polar gear is steel and is provided with a slip circle. The same drive is shown in the chapter on setting circles.

be obtained in quite a variety of sizes and ratios, and they are quite useful for getting around corners. As they are made both right and left hand, they can also be used to change the direction of rotation, if necessary.

There are a number of synchronous motors on the market which may be used for driving telescopes. The Bodine Electric Co., Chicago, Ill., manufacture a 1/20 H.P. synchronous motor which has been used for a number of successful drives. It has ample power to handle the largest instruments, and is recommended for use with heavy telescopes which are equipped with plain bearings. This motor operates at 1800 r.p.m., when used on 60-cycle current.

A much smaller and less expensive synchronous motor, which still is

powerful enough for instruments up to 15″, can be obtained from Andrews Hardware and Metal Co., 334 South Main St., Los Angeles, Cal. These motors operate at 2400 r.p.m. on 60 cycles. Inquiries should be addressed to Motor Dept., Andrews Hardware Co., and should refer to the "Andrews Hardware Special Synchronous Motor for telescope drive."

The Warren Telechron Co., Ashland, Mass., manufacture synchronous

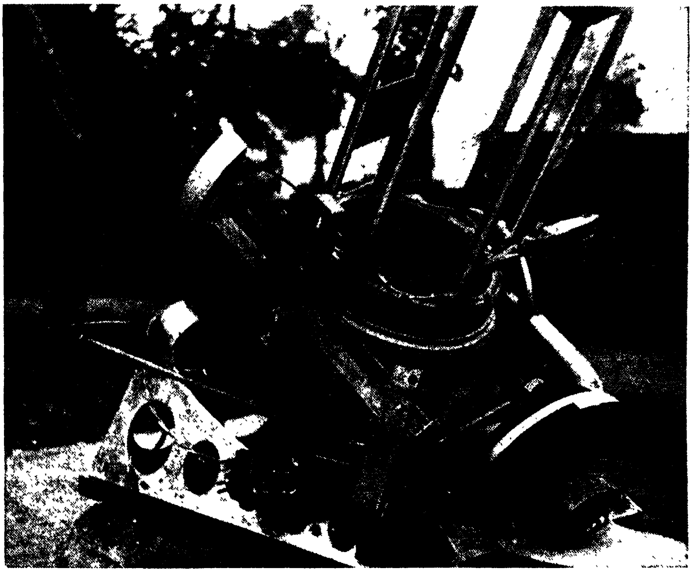


FIGURE 7

A 9″ telescope built by Dr. H. Page Bailey, of Riverside, California. Andrews Hardware synchronous motor used for drive. Guiding in R.A. is controlled by moving the main worm tangent to the worm wheel. Note spring for taking up slack on screw threads.

clock motors which have been used successfully for driving telescopes of moderate size. The ordinary Telechron motor which is used in most small clocks is not suitable for telescope drives, but a larger and more powerful motor, Type C2M, is available. The Type C2M Telechron is rated at 12 watts, and develops a torque of 2.0 inch-pounds, at 1 r.p.m.

The Hansen Mfg. Co., Princeton, Ind., also manufacture a small synchronous clock motor which should be suitable for driving a telescope of moderate size. Data regarding the torque of these motors is not at hand, but the motor seems to have a surprising amount of power, considering its small size. These motors are self-starting, and have a built-in gear box which reduces the speed to 1 r.p.m.

The Barber-Coleman Co., Rockford, Ill., can supply motors which are quite similar to the Andrews Hardware motors. No data on these motors is at hand, but the sample which I have examined seems to have power enough for telescopes up to 12″ or 15″ in diameter. This motor operates at 2400 r.p.m., on 60 cycles.

In any case where there might be a question as to the power of one of the small synchronous motors being adequate, two or more motors can be used in parallel. This system has been used at the McMath Observatory near Lake Angelus, Pontiac, Mich. Francis C. McMath, Henry S. Hulbert,

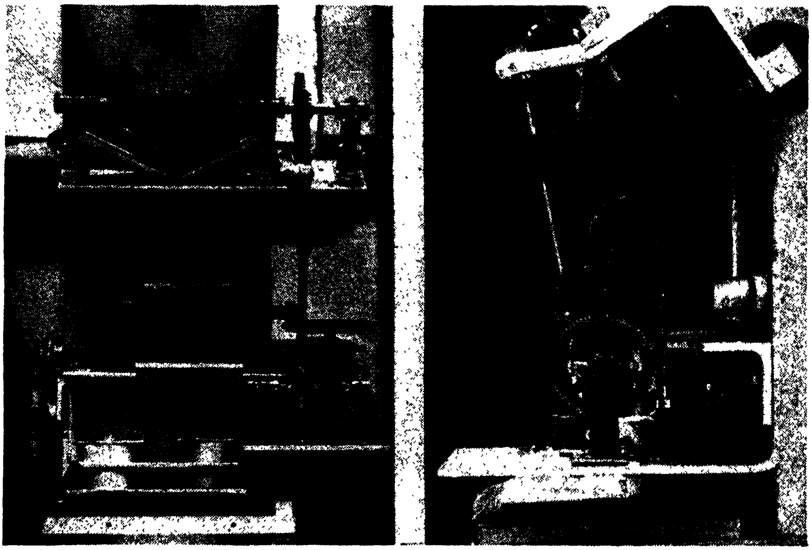


FIGURE 8

Left: Synchronous motor drive, with variable ratio friction drive for speed control. Built by Chas. A. Lower and Harold A. Lower. The drive is mounted on a base which is separate from the telescope, and is floated on rubber, in order to prevent vibration. Right: Method of mounting the friction disk. Note the rubber coupling, which prevents vibration from being transmitted to the telescope.

and Robert R. McMath have developed Telechron drives for several telescopes, and have used them for the very exacting work of celestial photography. These drives use two 12-watt Telechron motors, and have proved powerful enough to handle a telescope which, with the extra camera equipment, weighs over 1000 pounds.

The first of the McMath Telechron drives was equipped with a gear train which used a 365- and a 366-tooth spur gear for making the change from standard to sidereal time. The error involved in the use of these gears amounts to less than 1/10 second per hour from sidereal time, and is

less than the average error in the frequency of the alternating current on most power systems. It is reported that this drive showed no drift in right ascension during the period of an hour.

C. C. Chapman and H. Page Bailey, of Riverside, California, have equipped several telescopes with synchronous motor drives, using small motors obtained from the Andrews Hardware Co. These telescopes range from 9″ to 15″ in diameter, and in all cases the motors have proved amply powerful (Figure 7).

One method of avoiding the use of special gears in making the change from standard to sidereal time is to use a variable ratio friction drive at some point in the gear train. My father, Chas. A. Lower, and I have used this method in driving our double 12″ instrument which is used quite a bit for photography. The variable ratio friction drive not only makes the change from standard to sidereal time, but it permits changing the rate so as to follow the moon or a planet. This drive (Figure 8) has been in use for several years, has proved satisfactory even for long exposure photography, and has required no attention except occasional oiling. The motor used with this drive is a $\frac{1}{20}$ H.P. synchronous, which operates at 1800 r.p.m. The gear train is as follows:

Variable ratio friction drive, approximately 1 to 3.6; worm gear, 1 to 72; spiral gears, 1 to 2; worm gear, 1 to 50; worm gear, 1 to 100. The motor and first three stages of the reduction form a unit which is insulated from the telescope by sponge rubber. The shaft which connects the spiral gears to the 50-tooth worm gear which drives the main worm shaft, is interrupted by a rubber coupling which prevents transmission of vibration from the motor to the telescope.

The friction drive is quite simple. A roller of hard fiber, on the motor shaft, drives a friction disk which is faced with thin, hard, sole leather. This friction disk is forced against the roller by means of a spring which is located between the shaft of the friction disk and the shaft which carries the first worm. These two shafts are joined by a splined connection which permits a small amount of vertical movement of the friction disk, yet transmits only rotary motion to the worm shaft. Change in the ratio of the drive is accomplished by moving the motor axially on sliding ways similar to the cross-feed of a lathe, by means of a screw which is turned by a flexible shaft. Moving the roller nearer to the center of the disk speeds up the telescope; moving it the other way slows the rate. As the flexible shaft is long enough to be within easy reach, regardless of the position of the eyepiece, this enables one to guide in right ascension. The control is not critical, and one may turn the flexible shaft half a turn or so at a time without a star jumping off of the cross-wires. As the speed of this drive depends on the position of the roller with regard to the center of the friction disk, no end play in the motor shaft can be permitted, as this would affect the clock rate.

As can be seen from the photograph, this drive requires very little machine work, as it is mainly constructed from easily obtained standard parts.

There are a great many different types of telescopes, and for that reason no attempt has been made in this chapter to give detailed directions for constructing any particular clock drive. Practically all drives are in some degree special, and must be made to suit the particular instrument which is to be driven. However, I hope that the descriptions and photos of drives which have been constructed by various amateurs will encourage others to

Photo by Ernest P. Maier

Left to right: Charles A. Lower; the drive shown in Figure 8, attached to a mounting which carries a 12" Cassegrainian and a 12" Newtonian—both instruments may be used for photography; the author.

tackle the many problems which are encountered in the building of a good clock drive.

Additional information on this subject may be found in the following publications.

"A Manual of Celestial Photography," by Edward S. King.

"The Telescope," by Louis Bell.

Popular Astronomy, October, 1930 (McMath, "McMath-Hulbert Telechron Driving Clock"—6 pp.).

Publications of the University of Michigan, Vol. 4, No. 4.

The Review of Scientific Instruments, Vol. 3, No. 9. (Sept. 1932), pp. 499–510; "Frequency Requirements and the Control of Frequency for Synchronous Motor Operation of Astronomical Telescopes."

Drives for Larger Telescopes

[EDITOR'S NOTE: The matter in the preceding chapter is aimed at the average amateur with an average-sized telescope, but a smaller number of amateurs—especially now that larger and larger telescopes are being made by amateurs—appear to desire ideas for more elaborate drives.

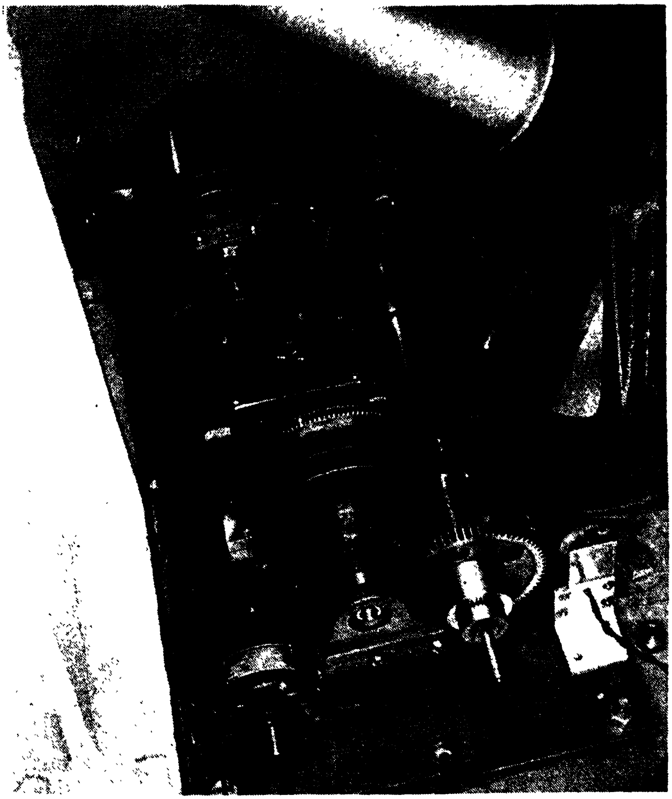


FIGURE 1

Drive for the telescope shown in Figure 2, made by Alan Gee and C. Carvel Diller, of Washington, D. C.

In cases where outside power is available but poorly synchronized, attention is called to the frequency controlled drive developed at the McMath-Hulbert Observatory, which is entirely independent of the system frequency

and voltage variations of the line. This was described in the *Publications of the Observatory of the University of Michigan,* Vol. V, No. 10.]

By Alan Gee, West Point, N. Y.: This drive (Figures 1 and 2), made for a 12½" fork type reflector (Figure 2), consists of three drives all working through the same drive gear. An 1800 r.p.m. synchronous motor powers the clock drive. The gearing from the motor to the polar axis is as

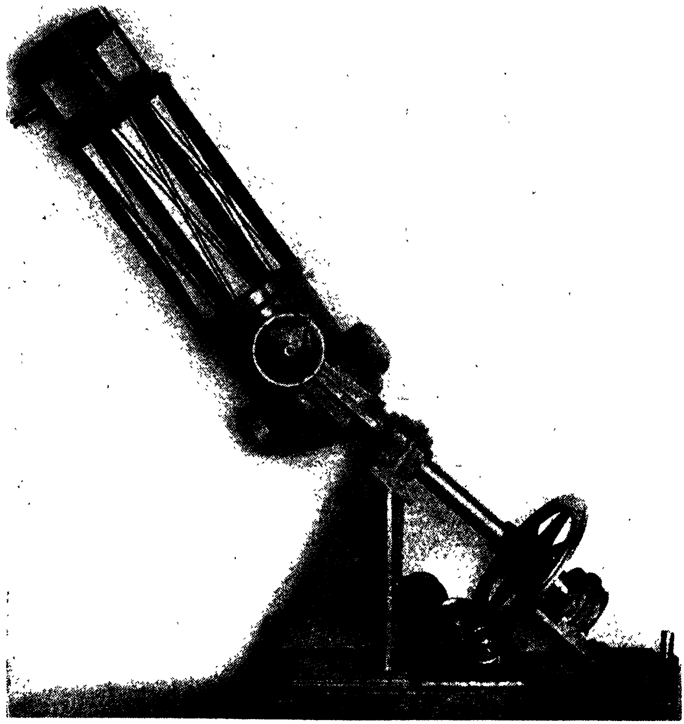


FIGURE 2

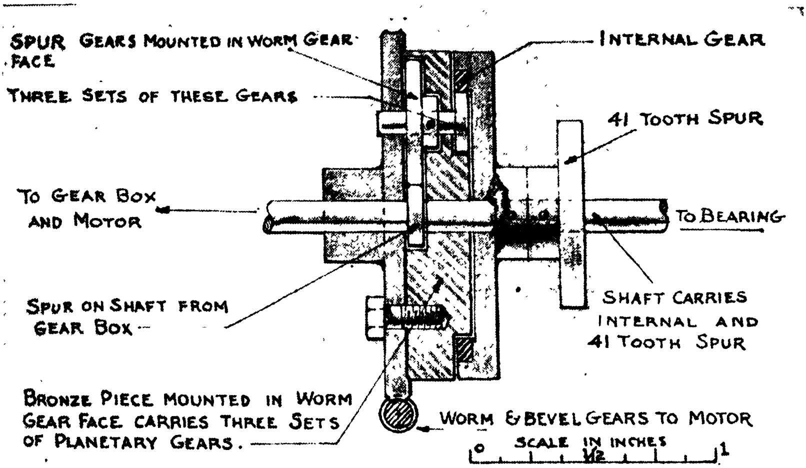
follows: 1:400, 1:8, 41:69, and 1:480. The 1:400 unit is a stock speed reducer containing two worm gears. The 1:8 reduction is through a small differential. A second reversible slow motion motor drives the cage of this differential to provide slow motion. The 41:69 reduction is through two, 16-pitch spur gears. The 1:480 reduction is the main drive worm, a 24-pitch, 20", cast iron gear driven by a 1" pitch diameter steel worm. This gear with worm was made to order by The Grant Gear Works for $36.00.

A third motor is connected to the driving worm through 1:12 reduction

gearing. When this motor is started, a small magnetic clutch, clearly shown in Figure 1, disengages the rest of the drive. The clutch automatically closes as soon as the motor stops. This is to provide fast motion.

These fast and slow motion motors are controlled through relays, by a push button unit carried in the hand.

The use of a differential such as was used in this clock (construction shown in Figure 3) is a good solution to the problem of having a clock drive and slow motion also. The slow motion here used is 2° per minute, while the



Drawing by Russell W. Porter, after Alan Gee

FIGURE 3

fast motion is 1 revolution per minute. The clock error is 1.76 seconds per sidereal day.

With the exception of the 16-pitch spur gears and drive gear, all the gears in the drives are stock, 24-pitch brass gears. The clock is mounted in self-alining ball bearings and adjustment is provided for the large spurs and the main drive gear. The use of ball bearings does away with objectionable end-play in the main worm shaft.

All gears in the clock except the 400:1 speed reducer (a Boston Gear Works product) came from Grant Gear Works. The synchronous motor is a 1/20 H.P. Westinghouse. The two small motors are series motors of 1/20 and 1/35 H.P. The relays used are modified E.A. auto horn relays and cost 29 cents each. The small clutch was made from the rear axle assembly of a bicycle.

Actual operation has shown this clock to be highly satisfactory. Push button controlled slow motions provide a great advantage over hand crank

motions, particularly for photography, in that they do away with the necessity of touching the telescope.

The following is a list of gear ratios for obtaining sidereal from standard time. They represent close approximations to the fraction $\frac{\text{86400.00 sec. solar day}}{\text{86164.09 sec. sidereal day}}$ and factors of the fractions.

	Error in Sec. per day	
$\frac{364}{363} = \frac{14 \times 26}{11 \times 33}$	$-$ 1.45	Can be obtained in brass stock gears.
$\frac{365}{364} = \frac{5 \times 73}{7 \times 52}$	$-$ .81	
$\frac{731}{729} = \frac{17 \times 43}{27 \times 27}$	$-$ .48	
$\frac{366}{365} = \frac{6 \times 61}{5 \times 73}$	$-$ .16	
$\frac{4029}{4018} = \frac{51 \times 79}{41 \times 98}$	+ .02	
$\frac{369}{368} = \frac{9 \times 41}{8 \times 46}$	+ 1.76 (ratio used in this clock)	

Boston Gear Works carries in stock 20 pitch "change gears" in any number of teeth, from 20 to 120. Prices are from \$.75 to \$1.85 (1935). The bore is 5/8", face 3/8" and no hubs. Their bore is cut with double 1/8" keyways.—*West Point, N. Y.*

By Joseph E. Boehm, Chicago, Illinois: The requirements of this clock drive (Figure 4) were to drive my 14" reflector (Figure 5), the moving parts of which weigh 400 pounds, with sufficient accuracy for long exposure photography. Inasmuch as these exposures would run to 3 hours or more, a drive having a minimum of mechanical errors, as well as reliability and smoothness of operation, was required.

Therefore, a polar axis worm gear having a large number of teeth was chosen in order to secure sufficient accuracy, and a special attempt was made to provide a strong and rigid support for the mechanism, well-mounted and close-fitting bearings, with gears, shafts, etc., of ample proportions to avoid flexures and vibration.

All the gears, except the worms, are of bronze; the shafts and worms are

stainless steel, while the bearings are phosphor bronze. The shafting used is of the type that comes ground to size.

The gear reductions, starting with the 1800 r.p.m. motor, are 45:1, 144:1, and 399:1, the latter being the large 25″ gear on the polar axis. The gearing

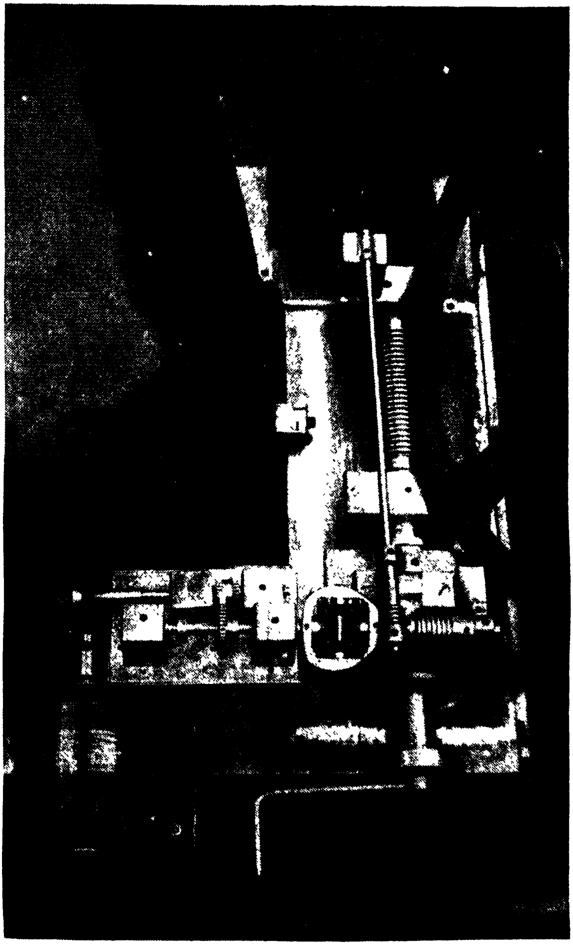


FIGURE 4

Drive for the telescope shown in Figure 5, made by Joseph E. Boehm of Chicago and mounted in an observatory at Lake Geneva, Wisconsin.

was first calculated to solar time, temporarily adopting 400 teeth for the large gear, then, by merely substituting 399 teeth, corrections were obtained for both stellar time and atmospheric refraction, the latter being an approximate 1 second per hour losing rate.

The large 399-tooth, 25″, bronze worm gear is 16-pitch, has a 1″ face, and weighs 60 pounds. It was made, together with its 1¾″ × 5″ mating stainless steel worm, by the D. O. James Mfg. Co., Chicago, after several widely varying quotations had been received from various concerns (Cost, 1933, worm gear \$23, worm \$7).

FIGURE 5

Since the large gear is rigidly fastened to the polar axis shaft, a hand crank of 4″ radius at one end of the ⅞″ main worm shaft provides for fast motion in R.A. This shaft also carries a clutch, as well as the 144-tooth, 24-pitch worm gear. This gear is free to idle about the shaft when the clutch is disengaged.

The clutch is a multi-toothed, disengageable spline, formed by a 56-tooth, 32 pitch, ring gear meshing with a spur gear of the same size. The ring gear is attached to the 144-tooth gear while the spur gear revolves with the

main worm shaft, but can be shifted by hand to disengage the two gears when desired. A small clamp screw holds the gears either in or out of mesh. This clutch is simple, inexpensive and foolproof.

The $1/150$ H.P. ball-bearing synchronous motor is mounted on sponge rubber to reduce vibration. The worm for the 45-tooth, 32-pitch, reduction gear is mounted directly on the motor shaft. This little motor handles the 400-pound load, with power to spare, and consumes only 25 watts. A similar, $1/75$ H.P. motor, temporarily installed, consumed 40 watts under the same load and vibrated considerably more, while a phonograph motor proved too weak.

A special lunar driving rate is provided by a small "gear shift" unit built into the drive. One shaft carries a 27- and a 28-tooth, 32-pitch spur gear, while a parallel shaft carries a 28-tooth gear which can be shifted by hand to engage either the 27- or the 28-tooth gear. When meshed 28-to-28 tooth, normal stellar rate is obtained, while 27-to-28 tooth gives an approximate lunar rate. An electric slow motion in R. A. is included in the drive. This consists of a constant-mesh differential unit, similar in principle to an automobile rear axle assembly, driven by a separate $1/40$ H.P. reversible electric motor having controls near the telescope eyepiece. This unit permits accelerating or retarding the driving rate at will. Along with the "moon gear-shift," the differential is built into the drive between the 45- and 144-tooth reduction gears. Thus, having to travel through two large reductions before reaching the polar axis, any small mechanical errors in these two units will be quite negligible in effect. Normal synchronous drive is straight through the differential assembly, the frame supporting the two pinions remaining at rest. The direction of rotation is, of course, reversed in passing through this assembly. When slow motion is desired, the 1800 r.p.m. motor, operating through a 20-to-1 worm reduction, rotates the pinion frame. The 20-tooth worm gear is attached to the pinion frame, while the worm is coupled to the motor. This worm also serves to lock the pinion frame in a fixed position when the slow motor is not being used. All gears are 32-pitch. This slow motion unit has proved extremely efficient and convenient to use. Operated at twice the synchronous driving rate, it gives very fine driving control for photographic or similar use. For random visual use a higher operating speed would be more suitable.

The base for the drive mechanism is of welded angle iron, and weighs 75 pounds, including the husky bearing supports. Bearings are "Bunting" phosphor bronze bearing bushings, which were first closely fitted to their respective shafts. Then—the shafts still in place—the bushings were properly positioned and soldered to their support posts. Cutting oil grooves and a little running-in completed the job. These bearings are inexpensive and efficient.

The entire drive mechanism, including the large polar axis gear, is protected by a dust- and oil-tight metal housing having a removable inspection cover. The gears and bearings operate in a constant bath of oil. Heavy oil, such as fluid-type automobile transmission oil, has been found to be the most satisfactory, giving quiet and smooth operation.—*3511 N. Seminary Ave.*

Hand-wound Spring Drives for Telescopes—a Composite Chapter

[EDITOR'S NOTE: The chapter which follows is a composite of several amateurs' experience with hand-wound talking machine motors for drives in R.A. Not everyone has access to synchronized current for an electric drive, or even wishes to install that kind of drive. Moreover, the spring motor drive is a good one.]

O. B. Darbishire, Shirley, Croydon, Surrey, England: An ordinary clockwork gramophone motor has just the properties required for a driving clock.

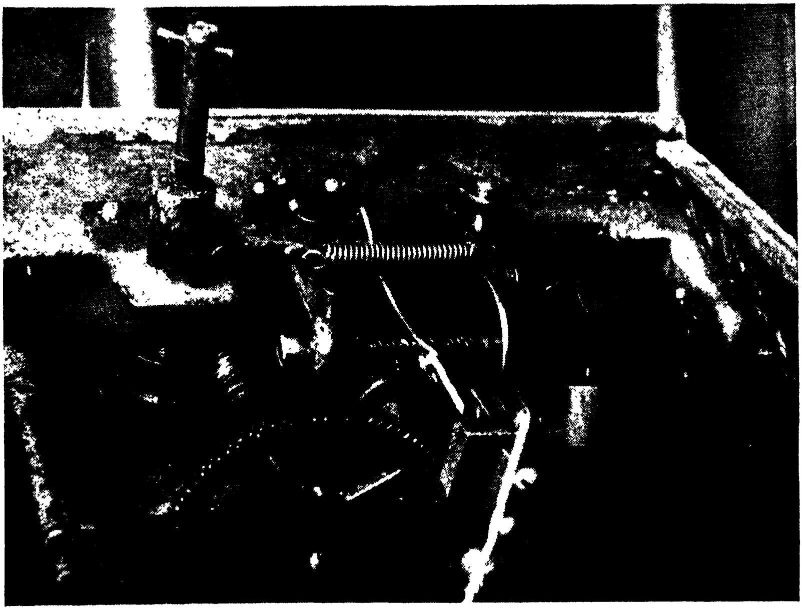


FIGURE 1

It has plenty of power, and its speed can be accurately controlled. A large double-spring motor was accordingly bought, and the following alterations made.

The governor weights were taken off and were replaced by heavier ones made from pieces of brass rod 7/8″ diameter by 5/8″ long. This, with a normal setting of the speed regulator, allowed the motor to run steadily at about one third of its usual speed, and to keep going for about 25 minutes at one wind. These oversize weights are shown near the right, in Figure 1.

The speed regulator was fitted with a sensitive screw adjusting device.

This consists of a small brass block screwed to the frame of the motor with a piece of screwed rod passing through it and bearing on the regulating lever. At the same time a strong spiral spring was fitted to make the regulator act more positively, and a simple cord and pulley device was added for temporarily increasing the speed without disturbing the adjustment. The spring and cord are shown in the left-hand part of Figure 2. Figure 1 also shows the pulley.

A worm drive was taken off the spindle which drives the turn table spindle. With the motor slowed down as described, this spindle runs at about 3 r.p.m. and a worm gearing into a 24-tooth worm wheel gave the

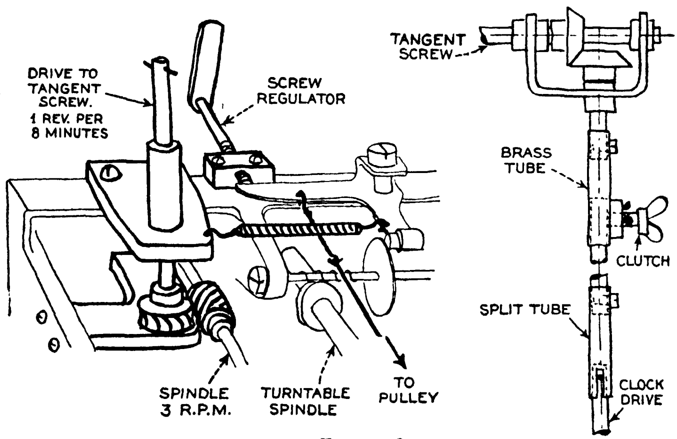


FIGURE 2

right speed for a 180-tooth wheel on the polar axis. It is only necessary to choose the right worm ratio to suit mountings having a different number of teeth on the polar gear.

The drive from the worm wheel on the clock is taken through a kind of clutch, shown in Figure 2, at the right, and then through a pair of bevel wheels to the tangent screw. The clutch is simply a kind of sleeve fitted with a set screw. When the screw is loosened the clock drive is not transmitted, and the slow motion can be worked by hand. For *small* adjustments in R. A., when using high powers, the clutch is just eased open a bit until the heavenly body has caught up, or the speeding-up cord is pulled until the motor has caught up, as the case may be. These two gadgets may be left out if the equatorial is fitted with a separate slow motion in R. A., independent of the clock drive.—*33 Wickham Avenue.*

George Meighan, Dover, New Jersey: The clockwork of my drive is a Victor combination spring motor and weight-driven assembly. The speed of the motor is reduced by a train of gears mounted within and on the side

of the pedestal (Figure 3, at the right). This train drives a drum around which one end of a belt is wound. The belt goes over the pulley on the polar axis and is kept taut by means of a weight on its other end. As the drum turns, the belt is unwound, causing the weight to drop slowly and rotate the pulley, which is connected by miter gears to the polar axis shaft.

A later communication: The drive shown in the photograph (Figure 3) has been dismantled, being unsatisfactory. Although this drive worked well, it had some disadvantages. [It is often as useful to know certain disadvantages in advance, as it is merely to know what final solution worked

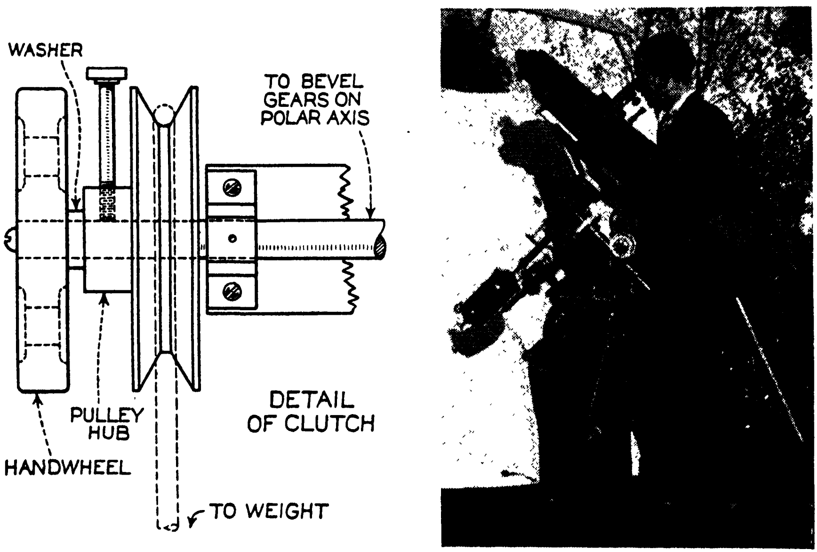


FIGURE 3

satisfactorily without being told of the grief that came before. Hence the inclusion of both items with regard to this drive.—*Ed.*]. First, I could not get it to run properly more than eight minutes without rewinding, which was a nuisance. Secondly, being mounted in the base of my telescope, it shook everything when I rewound it. These drawbacks could, of course, be overcome by using a larger spring and mounting the entire system on a separate base.

The essential advantage of this drive lies in the method of transmitting power to the polar axis. It requires less power in the spring motor, because most of the work of turning the polar axis is done by the weight. Then, again, the whole clockwork can easily be mounted at any distance from the telescope proper, by lengthening the belt, thereby eliminating vibration.

I include a diagram (Figure 3, left) of the simple clutch used to permit adjustments of the polar axis without disturbing the clockwork. By tightening the thumbscrew the pulley is made to engage the shaft and turn the polar axis by clockwork. By loosening the same screw the pulley rides free on the shaft, and adjustments may be made by means of the hand wheel, independent of the clockwork. This assembly is located near the polar axis shaft, in the photograph, where it shows in white.—*R.D. 1.*

Victor E. Maier, Secretary, Indianapolis Amateur Astronomers Association, Indianapolis, Indiana: For those who do not have access to a steady source of electric power, or whose hobby budget will not afford a synchronous

Photos by Ernest P. Maier

FIGURE 4

motor the spring-driven phonograph motor offers everything required of an excellent motor-drive. And, in addition, it opens a whole new field of kinks on which mechanical fans can outlet their ability.

The universally bewailed shortcoming of the phonograph motor is the fact that many of them are designed to run only long enough to play one or two records—5 or 10 minutes—and then must be rewound. There are several ways of lessening this inconvenience, such as introducing changes to enable the motor to run slower, or letting weights do part of the work, etc. One of the best of these dodges is the multiple spring motor, shown in Figure 4.

This Columbia motor has three springs working in tandem and, when fully wound, will run steadily for 45 minutes. This is long enough for the photography of many celestial objects, but even this need not prevent making a longer exposure. When mounted on a solid pier, preferably of reinforced concrete, rewinding can be accomplished in 30 seconds, without disturbing

the guiding operation. In this way the exposure can be prolonged until the night, or the operator, gives out.

The Columbia motor has fewer parts than any I have yet seen. A helical gear drives a 4-thread worm cut on the spindle. A small gear on this shaft drives the fly-ball governor by means of a similar worm. The only remaining part is the speed adjustment, which allows an infinitely graduated selec-

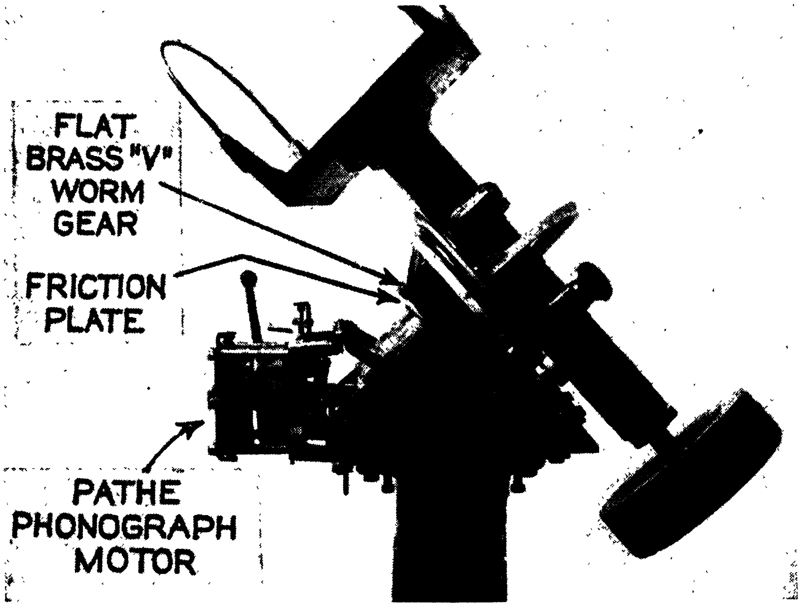


FIGURE 5

Attention is called to the McCartney mounting, of the Everest "Town Pump" type. It starts with a rear axle differential carrier for the polar axis. This automobile part is ideal for the purpose, as it has two axes at right angles, and the declination axis can be large. Only a few makes of cars have suitable carriers; the old Chevrolet carriers are excellent. This carrier was riveted to a torque tube. This mounting compares well with some of those described by Porter, in "A.T.M.," chapter on "Design of Mountings," where large cross-section in the axis shafts is urged.

tion of speeds. A train of gears can be easily computed, which will turn the polar axis one revolution per sidereal day. Worm gears were used in this drive, because of their superior smoothness. The diameter of the gear on the polar axis should always be as large as possible, usually about the same as the diameter of the telescope itself. The one shown is a stock, 32-pitch spur gear, driven by a worm mounted at an angle, so that the threads of the worm are parallel to the perpendicular teeth of the spur. This arrange-

ment works surprisingly well and was selected because a regular worm gear of this diameter and fine pitch would have to be especially cut, making it much more expensive. A little extra care in mounting the worm is all that is necessary to make a spur gear run as well as a worm gear, at this slow speed. A clamping clutch on the hub of the large gear completes the assembly.

In these days of radio popularity, an old phonograph motor may be had almost for the asking, and its marvelous smoothness and silent operation are a wonderful satisfaction, not to mention the fun of adapting it to your instrument.—*1306 Parker Avenue.*

E. B. McCartney, Mineola, N. Y.: The "Hempstead Hydrant" mounting

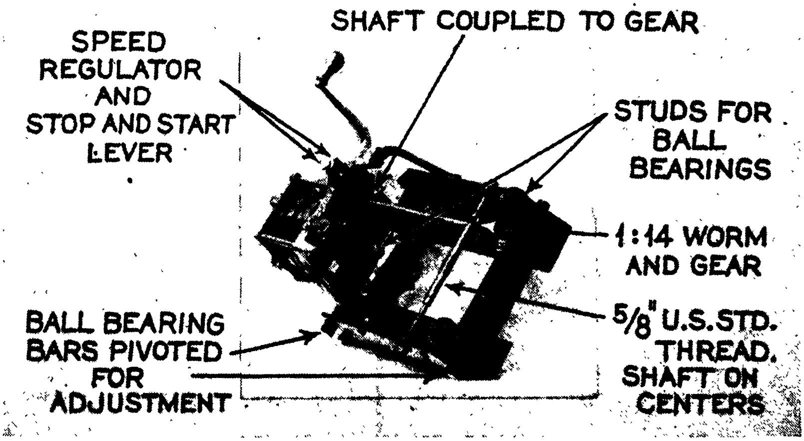


FIGURE 6

shown in Figure 5 has a phonograph motor drive, with the motor turned up on its side in order to expose the gears and to bring the governor shaft vertical. In this position the motor is almost exactly an astronomical driving clock, and by adding a shut-off lever and adjusting screw the speed can be very closely regulated. Mine runs for 50 minutes at 40 percent of its normal speed, which gives the drive shaft 2 r.p.m. First reduction worm and gear are 14 to 1 and polar axis worm gear has 205 teeth with single thread worm. This produces one revolution of the polar axis in 1435 minutes, or a minute off per sidereal day. No vibration is apparent from the motor, even when using magnification of 425 times, although the motor is bolted to the base and no damping pads are used. Also, the motor can be wound without disturbing the field of view of a ½" eyepiece. I have not tried photography but for visual work I can't see where a much better outfit can be had at any reasonable price. I paid a dollar for the motor and a dollar for the differ-

ential carrier and, excepting eyepieces and finder, the whole telescope cost about $25.

Connection of motor to telescope drive is very simple and direct, as per Figure 6, and the drive is taken off a gear which originally turned 5 r.p.m.

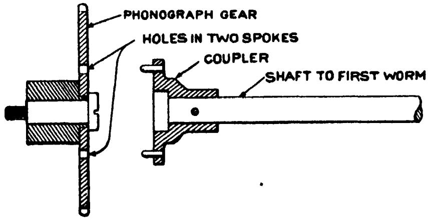


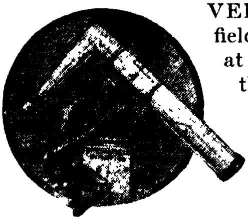
FIGURE 7

Enlarged drawing of the part in Figure 6, which is marked "shaft coupled to gear."

but when slowed down turns 2 r.p.m. This is far simpler than taking drive off the record spindle at 78 r.p.m. and reducing to proper speed. The motor has ample power for the purpose and I plan to use this mounting for any telescope I might build up to 12".—*76 Roslyn Road.*

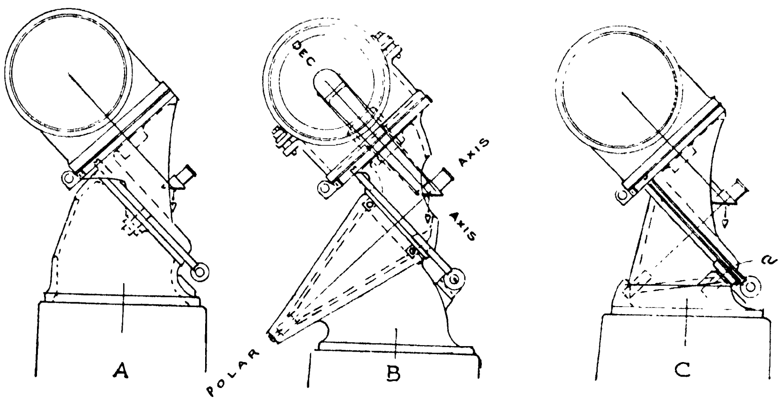
The Springfield Mounting *

By Russell W. Porter
Pasadena, California



OVER 15 years ago—in 1920, to be exact—the first Springfield mounting, so-called, was put together and tried out at *Stellafane*. Since then many amateurs have chosen this type of support for their telescopes. They seem to have taken very kindly to the comfort afforded by a fixed eyepiece, with all controls and setting circles within easy reach. However, were I to redesign this mounting—as in fact I shall be doing in these chapters—there would be several weak spots in the original design to be strengthened, also a few worth while additions to be made, if the mirror maker really wishes to get the utmost in performance out of his hard-earned optical surfaces.

A "fixed" eyepiece in an equatorially mounted telescope must naturally be



All drawings by the author

Figure 1

Three forms of the Springfield mounting: A, the prototype; B and C, two suggested variants.

at or near the intersection of the two axes of revolution, for this is the only point that remains immovable. Since this region, in the familiar German type, is in the solid declination shaft, we must—for the declination axis—

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* The Springfield mounting was conceived, designed and developed by the author of the present contribution, and by him named for the Vermont community in which this was done. No direct mention of this fact having been made by him in "A.T.M.," it was believed by the undersigned that new readers of these books might overlook it—as appears actually to have been the case in some instances—unless it were openly stated by someone else, as is now done.—*Ed.*

have recourse to a wide track turning on a hollow stud. This will bring the focus of the mirror out into the open, where it can be handled by the eyepiece as easily as desired.

There are at least three different ways of defining the polar axis. *A,* Figure 1, is the original Springfield mounting.* Both axes are defined by broad plates rotating on central studs. Figure 1, *B,* has a polar axis shaft with two closed bearings, the upper being by far the larger, and running on balls. Figure 1, *C,* defines the polar axis by using a wide track for its upper bearing—open, supported by two rolls *a,* 90° apart. The lower bearing is a thrust bearing in the axis itself.

All three of these types may have a common hand or clock (motor) drive

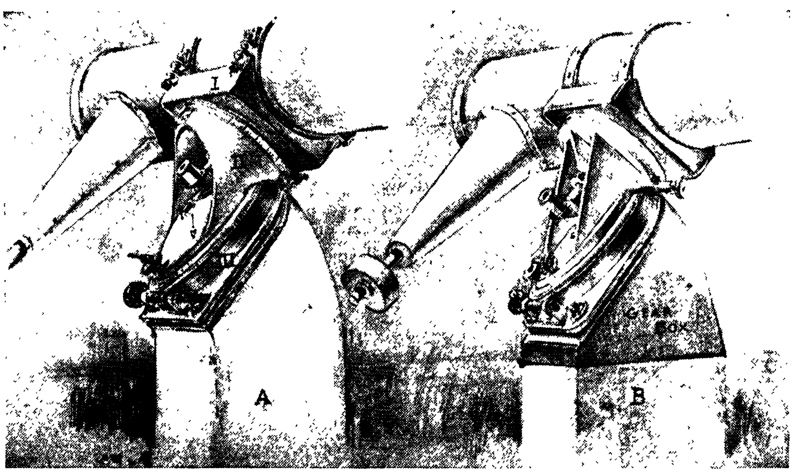


FIGURE 2

Two designs for the Springfield mounting: A and B differ in several details described in the text. B is a clock driven type.

in R. A., shown here as worm wheels carrying slip ring circles to be explained later on. Which one of the three do you prefer? Each one has its strong and weak points. I am naturally inclined to stick to the old prototype, *A,* and will do so from now on.

To cover two possible cases that may arise (to be mentioned further in a later chapter), two designs, *A* and *B,* of Figure 2 are here submitted. We will henceforth designate the three main castings as I, II, and III, as originally numbered in "A.T.M." and shown in Figure 2, *A*. *A* presupposes a

* Possibly a simpler way to obtain slow motion in R. A. is to attach this stud to a thin circular plate between 11 and the worm wheel, thus obviating the necessity of cutting the groove in the worm wheel.

hand drive, only. *B* includes a gear box for whatever drive is used. Casting II of *A* requires core boxes for the patterns (see later chapter on patterns). Casting II of *B* has no coring, which considerably simplifies the pattern making. *A* shows the telescope tube attached to I by means of exposed push-pull screws. In *B* these screws are placed inside the tube, thus making a little cleaner looking job. In both designs all the machining can be done on a 13″ lathe. To accomplish this the tracks on I and III have had to be made separately and later screwed to I and III. We will begin with a detailed description, taking first model *B*. This is shown in an assembly section in Figure 3.

General Description: When the tube and all moving parts have been duly counterpoised, their combined weight is concentrated at 1, Figure 3, where the Dec. and R. A. axes intersect. The center of mass of a mounting of this type must be near this point, if the instrument is to function properly. Its weight is resting on stud 2, at 3, the axis being defined by the wide equatorial track 4. The adjusting screw 5 will permit most of the load to be carried at 3, and the balance evenly distributed over the defining track 4.

Setting in declination remains the same as in the original design: viz, by a screw 6, bearing against a spur projecting from the circular plate 7. Of course a worm wheel may be substituted here if desired. The necessary friction between castings I and II is had with nut 8. Washer 9 has an internal spur (see Figure 2 in the chapter on machining) that prevents the nut from unscrewing, and inside this washer is a fiber washer, 10.

Now for the drive in R. A. While Figure 3 shows no motor, this is represented in the final chapter of the series, in Figure 1, at *A*. The drive is through worm 11 and wheel 12. The worm wheel runs freely on its seat, carrying I, II and the telescope with it. All moving parts now turn as a single unit, the telescope following whatever object it is on. The tube may be swung from one part of the heavens to another, as well as in declination, without disturbing the clock drive.

When it is desired to move the telescope independently of the clock, as when a star is brought to the center of the field—in other words, careful setting in R. A.—this is accomplished as follows. In the worm wheel is the circular groove 13, and inserted in this slot is a square-headed stud 14, which may be clamped to the wheel by the screw 15. An opposing screw 17 will then push against this stud and the telescope may be moved back and forth at will in R. A. without disturbing the clock.

The importance of this will now become apparent. 18 is a slip ring sunk into the worm wheel, graduated into 4- or 5-minute time intervals and numbered clockwise from 0 to 24 hours. By means of this slip ring and the independent slow motion already described, we have the ideal way of preserving star time throughout the evening, and by the same means any object whose R. A. is known may be readily found. The circle is set once for all at the beginning of the evening, by setting on any bright star and turning the slip ring by hand until the star's R. A. as given on the ring comes opposite the index on II (not shown on Figure 3 but see Figure 1*a* in the later chapter

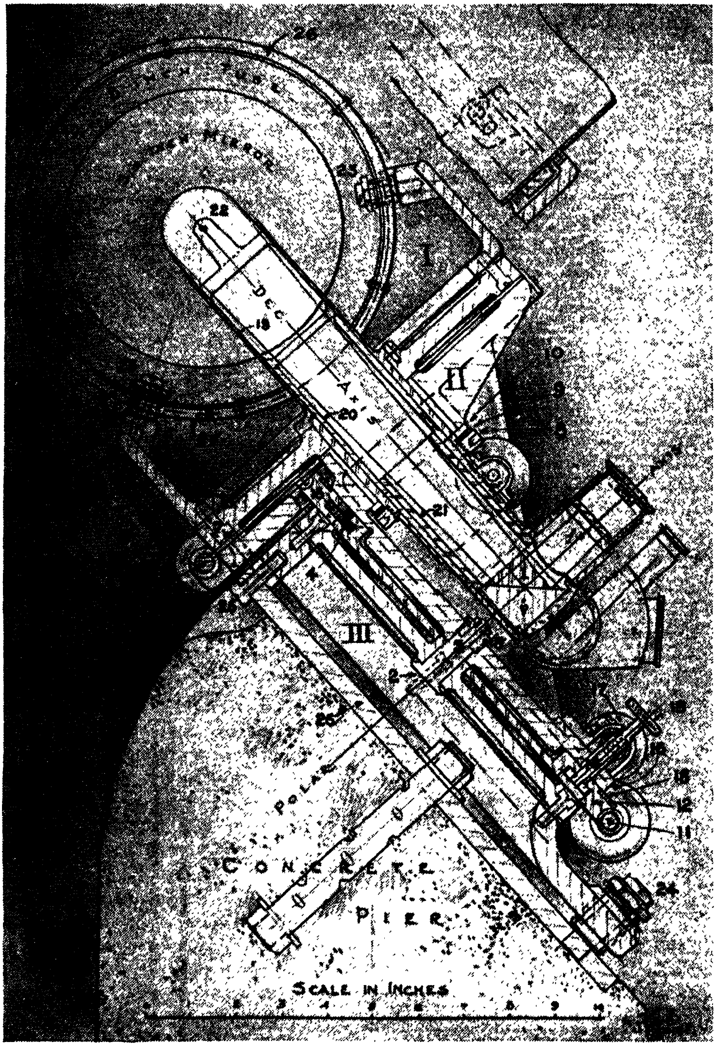


FIGURE 3

on machining, at *a,* upper right-hand corner). The slip ring circle is then left undisturbed, the clock (motor) keeping it always "in step" with the stars. It is, in fact, a sidereal clock giving local sidereal time. To pick up

Left: Russell W. Porter, designer of the Springfield mounting and, right, Fred B. Ferson of Biloxi, Mississippi, who was the first to build the revised Porter Springfield mounting described in these chapters (See his chapter on "Molding and Casting"). Both photographs show the finished telescope. The manuscript of the chapters by Porter was lent to Ferson several months in advance of publication. During the middle months of 1936 Ferson built the patterns, made the castings, machined them and assembled the mounting. This was done to detect, before publication if possible, all errors that might be hidden in the specifications. The photograph (right) was taken by Mr. Porter in August 1936, when he inspected the finished mounting at Biloxi. "Actually," Mr. Ferson writes, "the mounting, starting with some hunks of wood for patterns, making the patterns, molding, pouring, machining the castings and small parts, fitting all together and putting the telescope on the pier, could be done in about 75 days of night and holiday work. A good foundryman and machinist could do it more quickly; it all depends on the tools you have available. For example, I had no post drill or drill press, so when I wanted to use one I had to move the mountain to Mahomet."

any object, the tube is swung until the object's R. A., as shown on the ring, comes opposite index *a* in the cross-reference given above, using, of course, the slow motion thumb screw for close setting.

I hope that the method here outlined for settings in R. A., independent

of a clock or a watch, so that star time is always available (the same one described in "A.T.M.," chapter on design of mountings), will appeal to the fraternity as an effort well worth while incorporating into their mountings. Incidentally, for those who seek the ultimate in perfection, I suggest that all setting circles, hour circles and indexes may be stripped from the mounting altogether, and transferred to the walls of the observatory, where, with dials and counters hooked up electrically to the instrument drives and push buttons, the observer turns up his Dec. and R. A.—and behold, the object is right there in the eyepiece. Now that Selsyn and synchronous motors have arrived, the scheme is entirely practical, in fact it is now being installed in a moderately large telescope here in California.

The only other change in the old model is to combine the prisms and eyepieces in one unit, in order to collimate them more easily and accurately. This unit consists of three tubes 19, 20 and 21. 19 carries prism 22, and when adjusted to aline with the telescope tube, it is doweled to I, as shown. 20 is an adapter tube provided with focusing rack and pinion, for those who want it. 21 belongs to a diagonal provided with a multiple eyepiece. Probably there are some who would like to have their oculars combined in this way, so that comparisons in magnifications may be made quickly, without having to fumble about in the dark for an ocular that may be ultimately found somewhere in the grass.

In order that the mounting shown in Figure 3 could be machined on a 13″ lathe, as already mentioned, it was found necessary to make the tracks on I and III from separate pieces and, after machining, to screw them on as shown. 23 refers to four push-pull screws on the saddle, for alining the tube with the Dec. axis and prism 22. There are only two push-pull screws on the base, at 24. 26 is a plate grouted permanently to the concrete pier, referred to later on.

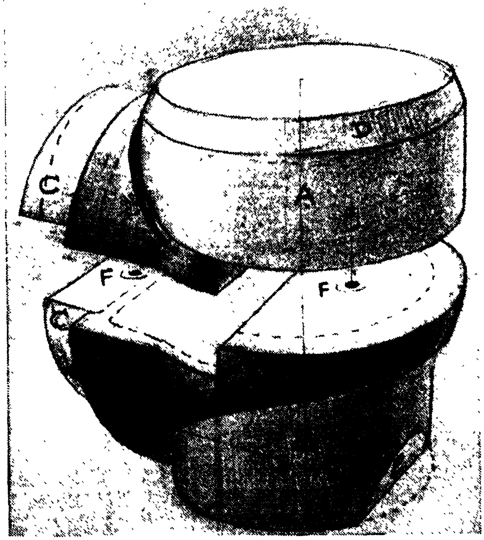
The mounting is shown carrying a 6″ mirror in an 8″ tube. At the scale given, it undoubtedly would carry an 8″ telescope, but I would prefer to increase the size of the support in proportion to the diameter of the mirror.

Figure 3 is a meridian section through the mounting and is inclined to the nadir suitably for an observer situated at latitude 42°, which passes through the denser populated part of the States. I mention this to show why the base casting projects so far beyond the remainder of the mounting. It is to bring the center of weight, at 1, well within the pier. This makes for stability.

The Springfield Mounting—Pattern Making *

By Russell W. Porter

One of the by-products of telescope making has proved to be the desire on the part of some amateurs to go the "whole hog," to the extent of making their own patterns for the castings of their mountings, and even trying to cast them. Although not a pattern-maker, I have had my fling at it, and will pass the experience on to the fraternity for what it is worth. Anyway, after having had my patterns returned many times from the foundry as



All drawings by the author

Figure 1

unworkable, and with the kindly aid of a telescope maker who was an expert machine tool pattern man, I was finally able to get castings that answered my purpose, and from my own patterns.

* The instructions presented in this chapter and the two on molding and casting which follow it, may be regarded not alone as pertaining to the Springfield mounting but to making small castings in general. Once the general methods of the work are learned, there will be other applications of it which the amateur can and no doubt will use in connection with telescope making. Those who have learned the trade, such as the author of the chapter on "Molding and Casting the Springfield Mounting," report that is is interesting work—or fun—in itself.—*Ed.*

The editor has asked that I take for an example the parts of the Springfield mounting. I will select as the most complicated of the three castings the one labeled II in Figure 2 of the previous chapter. But before going ahead and describing this particular pattern, it may pay us to look at the general subject of castings from the molder's viewpoint—for the tyro probably does not fully appreciate the hard and fast rules laid down by the molder, to assure a clean casting and one that has not been mutilated by a

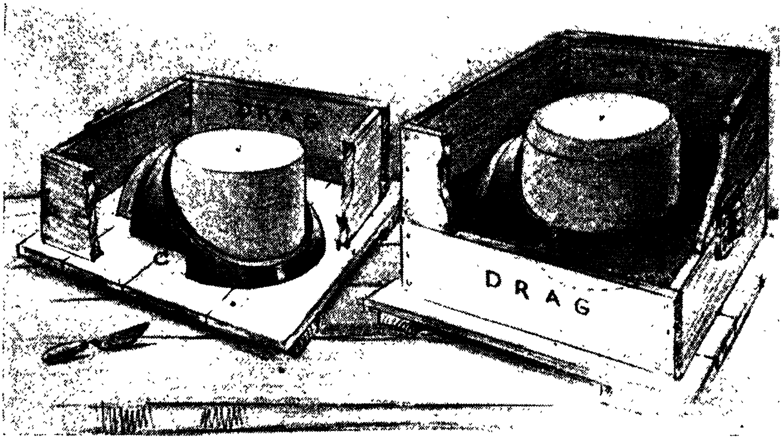


FIGURE 2

pattern that tears away the sand when it is drawn from the mold. To facilitate this viewpoint I have prepared the drawings shown in Figures 2, 3 and 6, which show the steps taken by the molder from the time he receives the pattern until the metal is ready to be poured.

He receives the pattern shown in Figure 1. This is the pattern we are later to construct. It is a split pattern; with the two parts shown slightly separated. The dark portions indicate parts of the object to be cast, and the lighter ones, labeled *A*, *B* and *C* (see also Figure 4), are core prints whose purpose will soon be made apparent. The molder takes the lower part of the pattern, turns it over and lays it on his molding board, as in Figure 2, at left. An affair like a box with the bottom knocked out, and called a "flask," is then laid on the board. Green sand is rammed firmly around the pattern, completely filling the flask. They call this lower flask the "drag." The sand is leveled off, covered with another molding board and the whole thing turned upside down. We now come to the right-hand drawing in Figure 2. The sand under the pattern (at *C*, left hand drawing) is cleared away and the other part of the pattern is placed in position, as shown at the right, same figure. The "cope" or upper flask is then added and more sand rammed in.

When the cope is lifted off, turned over and laid beside the drag, the patterns are "drawn" from the mold by driving a sharp-pointed bar into the pattern and rapping it smartly to expedite the withdrawal. The appearance will then be as in Figure 3.

Now for the reason for those core prints. A reference to the pattern drawing, Figure 4, will show that there are holes or undercuts on all three faces of the object, prohibiting their being molded and drawn from a solid pattern. Recourse is therefore had to inserts called cores. These cores fit

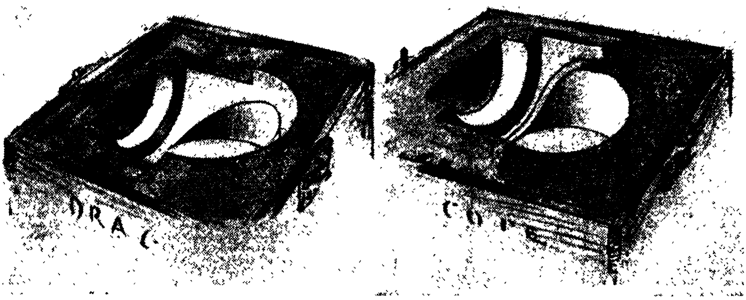


FIGURE 3

the impressions in the green sand, made by the prints of the pattern, and form the inner surfaces of the casting.

These cores are made by filling a core box (see Figure 5) with core sand impregnated with oil and a core compound, then ramming hard and leveling off with the top of the box. An iron plate is laid on the box and clamped thereto, and the plate and box are rolled over. The box is carefully lifted off, and the core on the plate goes into an oven and is baked hard. It can then be handled without breaking. This is called a "dry" sand core.

When the cores are inserted in the molds the appearance will be as in Figure 6. All that then remains is to "gate" the mold to provide a passage for the molten metal, when the molds are then reunited and ready for pouring. When you later dig out your child it will look somewhat like Figure 7—bearing a close resemblance to a cross between a bubbler fountain and a lavatory bowl looked at from underneath. It does not bear much resemblance to Figure 1, but it should now be fairly evident why the pattern is made as it is, and we can now go ahead intelligently and make it.

Without a wood-working lathe the pattern could, it is true, be produced, but it would be pretty nearly a whittling job and rather unsatisfactory. Let us assume that a lathe is available. The three core prints *A*, *B*, *C*, Figure 1, can all be turned and then carefully fitted to the parts painted black, securely glued and bradded thereto. See that the two halves of the pattern fit nicely

together and that the axes of the prints are properly alined, for there is little room for allowable error here, the walls of the castings being only about ¼" thick. To assist the free drawing of the pattern from the sand, give the prints a slight "draft" or batter of about 1/32" (Figure 8). Chamfer the top of print *A* (Figure 1), so that the core will easily find its mating part when lowered into the cope.

Slice off a piece, *E,* Figure 1, on the lower edge of print *B*. This must be duplicated in the core box, and is done in order to insure that the core

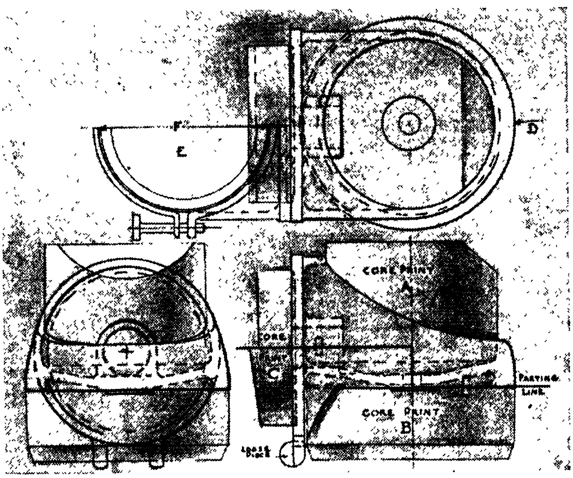


FIGURE 4

will be placed in the mold in one position alone. Be careful when placing the dowels *F, F*. One way to locate them is to drive a brad the size of a pin where you want the dowel to be, and cut off its head so that the brad protrudes 1/16". Then squeeze the two halves of the pattern together. This will leave an impression on the half opposite the brad. Then remove the brad and the indentations will indicate where the dowel holes are to be bored. Give the wood two coats of shellac—black (add lamp black) for the surfaces representing the casting and either red (add red ocher) or yellow for the core prints.

In the same way that it pays the mirror maker to give good measure to his fine grinding, so is it worth while to give your pattern as smooth a finished surface as possible. How many times have I watched an old molder, when given a new pattern with deep undercuts, run his finger down into the hole to see whether it is smooth or likely to tear the sand on drawing. A good final check to the pattern is to lay each half on the work bench (Figure

8) and go all around it with a try-square, to make sure there is everywhere sufficient draft for clean drawing.

But one core box is shown here—that for the core that goes with print *B*, Figure 1. The box, (Figure 5), must be so constructed, as already explained, that when filled with core sand it can be inverted and the box removed, leaving the core intact. Therefore a slight draft must be given the walls, and special care must be taken that the core is no larger than the

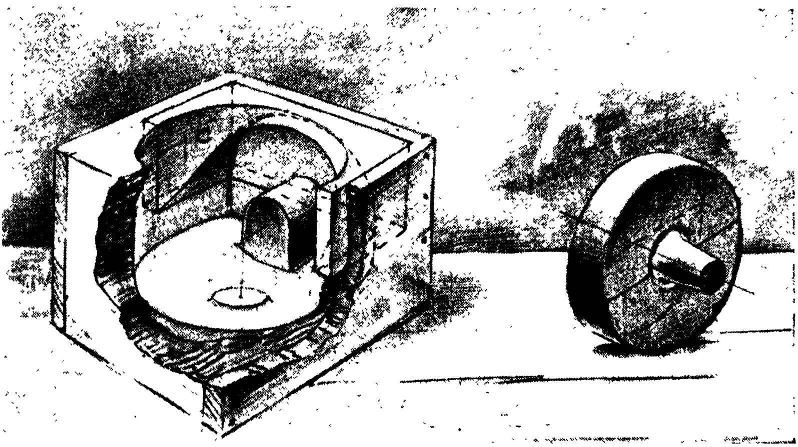


FIGURE 5

impression it is to enter in the green sand mold. Neither should it be so much smaller that it can shuck sideways, giving over-thin and over-thick walls adjoining it. In the core box in Figure 5, the core could not come out of the box unless a part of the box came out with it. Therefore a loose piece, *C*, is provided. When the sand in the box has been rammed hard and leveled off, and before the iron plate (already alluded to) is put on, the loose piece is drawn out and the impression left is filled with green sand—same as used in the mold. This is called "bedding in." The green sand acts as a support to the overhanging core sand while the box is being lifted off. Round all interior corners with fillets, using melted beeswax and a warm, rounded tool; or putty (good enough for a single casting); or the real thing of leather.

The core box for the *A* core is not shown, as it is similar to core *B*. The finished core *C*, Figure 4, is shown in Figure 5, at right. It may be cast in a half size box, half at a time, and the two halves cemented together afterward, as shown. Or a single box may be turned up on the lathe in one operation.

Baked cores leave a rougher surface on the casting than does green sand, but most of these core sand surfaces are out of sight.

As a final once-over, let us examine Figure 9, to see whether anything

FIGURE 6

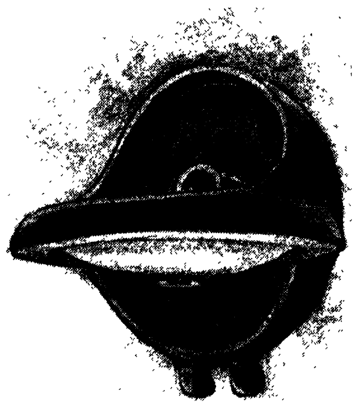


FIGURE 7

has been overlooked. In describing the core boxes and the draft required to get them off the cores, it is necessary to point out that the drafts on the core boxes and core prints of the pattern are opposite. In the drawing, the even gray tone is sand. The hatched surfaces are the cores. The white area remaining is the space to be filled with metal. Surfaces marked *D* are formed by the core prints *E* and *D* of Figure 4. The spaces between *D* and *E*

(Figure 9) therefore will be filled with useless metal which will have to be snagged off with a file or emery wheel. The two loose pieces are also indicated in Figure 9. *G* belongs to the pattern and after sand is rammed

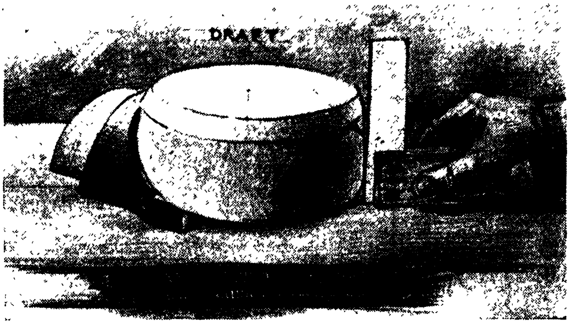


FIGURE 8

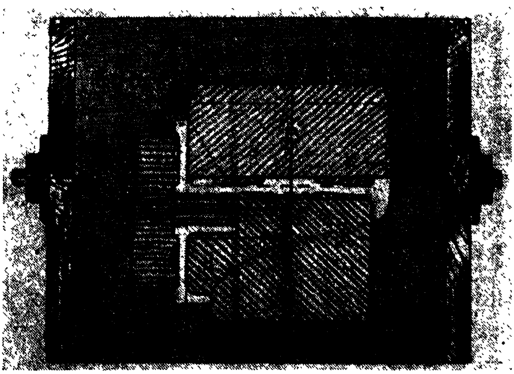


FIGURE 9

around it the two nails shown are removed, so that, on drawing the pattern the loose piece remains in the sand, to be picked out later. Likewise the loose piece in the core box is shown at *H*. The gating of the flask has not been indicated. It is the molder's job and does not greatly concern the patternmaker [next chapter.—*Ed.*].

Some little work is needed to prepare the rough casting for later machining operations. It is called "snagging," and means the use of a coarse file,

chisel, or emery wheel, to remove fins, burrs, and humps left where the casting was gated.

"Finish allowance": This means the excess of metal required for machining; 1/8" is usually considered sufficient.

"Shrinkage": Castings, on solidifying, become smaller than the pattern from which they were formed. Hence the patterns must be larger than the casting. The usual shop practice is to allow a shrinkage of 1/10" per foot for cast iron, 3/16" for brass and bronze, 5/32" for aluminum, and 1/4" for steel.

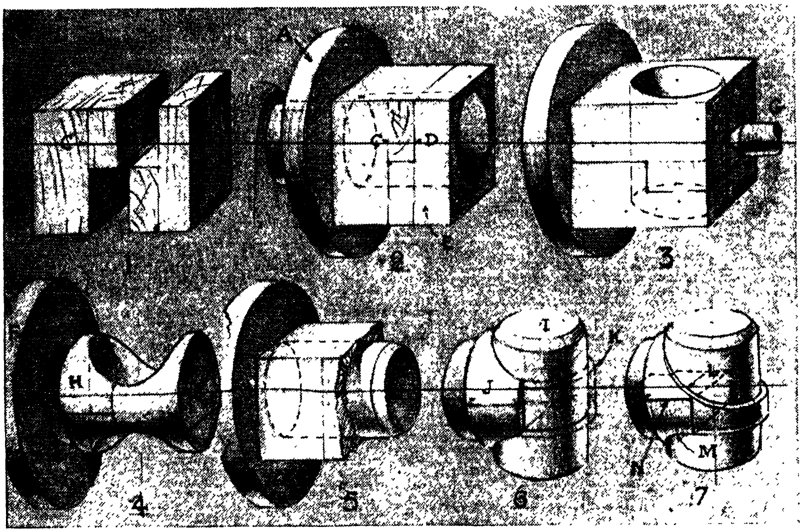


FIGURE 10

It is interesting to be told that, as castings increase in size, the shrinkage seems to diminish. And so, in so far as amateur telescope castings go, the shrinkage is almost negligible. But if track *D,* Figure 4, is to be a foot in diameter, the pattern should be made as much larger as is indicated by the above figures, depending on the metal chosen.

In order to make a wooden pattern retain its shape it is built up out of several pieces glued together, either in layers with crossed grains or in sectors (pie-shaped pieces) radiating from a common center.

No scale has been indicated or dimensions given on the pattern drawing. The size chosen depends, of course, on the weight of the telescope tube to be supported. An end view of the tube is shown at *E,* Figure 4, and the scale of the mounting may be chosen accordingly. If the mirror is a 6" one, the tube will be 7" or 8" in diameter, which gives the dimensions shown at *F,* and this furnishes a scale for the drawing.

The other castings of the Springfield mounting, I and III, should give no trouble after the more difficult pattern for II has been licked. I, the saddle, requires no coring, and the pattern of III will be split along a vertical plane passing through the polar axis.

The wood usually used for patterns is clear sugar pine, which has the grain, hardness and texture to produce good pattern surfaces, and is easy to fabricate. It does not need to be clear, as the knotty parts of second growth pine can be discarded.

Making the actual pattern: This work will need a wooden face-plate *A*, in 2, Figure 10, attached to the head stock spindle of the lathe. One way

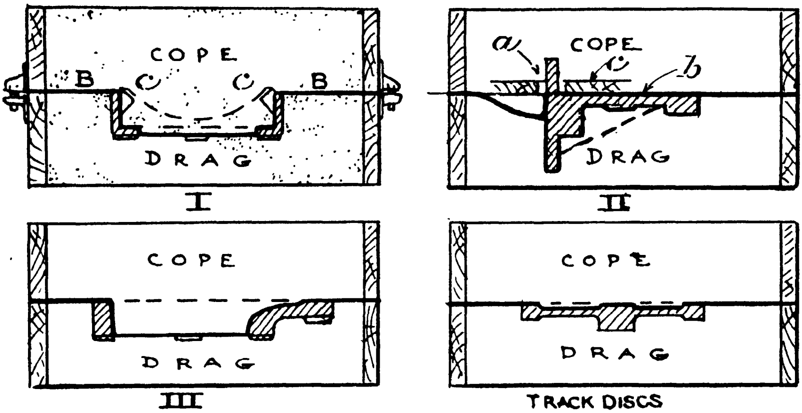


FIGURE 11

of fabricating the pattern is as follows. (Not being a pattern maker myself, the successive steps shown in the figure may not be strictly orthodox or standard practice, but they will serve.)

1—(See Figure 10: The numbered steps below correspond to the numbered drawings in this figure.) The blank is prepared by gluing together pieces of soft pine, as shown, with their grain crossed to prevent warping. In the 6″ mounting the offset *C D* is $1\frac{5}{8}$″. These two mating parts are now glued together—but first insert a sheet of newspaper between, before joining them. This will allow them to be split apart without injury, after operation 4.

2—Screw to face-plate and bore out hole. Toenailing (where the tail center cannot be used) is rather risky.

3—Remove, and fasten side *E* to face-plate. This is preparatory to operation 4.

4—It will be seen that there is not much wood left at *F*, in 4, so see that the holding screws come within this area. Use the tail center *G*, in 3. After turning, cut off on line *H*.

5—This is simply turning up the cylinder *I* of 6. Don't forget the bevel.

6—Make the cylinder long enough so that, when cut in two, the two parts may be fitted to *J*, as shown. Glue securely to *J*.

7—The final step is to glue on the ring *K*, of 6, and sweep out the curves *L* and *M* with your jack-knife. This split pattern, thus formed, parts along the heavy line *N*. It is ready now for the dowels and shellac.

Casting: To indicate how the patterns that go with this mounting are drawn from the cope and drag (see also Ferson's chapter on casting), Figure 11 is included.

In I, the heavy lines *B, B,* represent the parting between the flasks. There are four loose pieces at *c, c.* The remaining patterns have no loose pieces.

In II, cut a hole in the remaining board *c,* so as to allow that part of the pattern at *a* to pass through, and let the broad surface at *b* rest on the board while ramming the sand.

In III, the base—track disks—two required. The pattern is a simple job of lathe turning.

Should any one wish to read up on patterns, he will find a standard work in "Pattern Making," by Shelly (1920).—*July 9, 1935.*

Molding and Casting Springfield Mounting Parts

By Fred B. Ferson
Biloxi, Mississippi

[Editor's Note: Of the several adjacent chapters on pattern making, molding, machining and so on, all based mainly on the Springfield mounting, the present one on casting was received first, and the others were afterward written and assembled around it. Mr. Ferson had built what he supposed was a Porter Springfield mounting, working from some blueprints, but it was actually a Springfield "type" mounting. This situation made it evident that detailed instructions making it possible from first to last to build the Porter Springfield mounting were needed, and when by request Mr. Porter prepared these, he also revised the older form of his mounting. It was thought that some of the Springfield type mountings had been perhaps too light—not sufficiently massive. Others perhaps lacked artistic lines, but this was due very largely to the fact that making the patterns and castings for the original Porter Springfield mounting had been a rather difficult job without detailed instructions—the artistic lines did not readily lend themselves to the uninstructed maker's skill. The amateur fraternity no doubt will extend thanks to Mr. Ferson for his original inspiration to send in, on reading in the Scientific American a general request for material suitable for the present volume, some "instructions for molding the parts of a mounting," since the present chapters would scarcely have been written had he not originally thought to do so, thus, as it were, starting the ball rolling.]

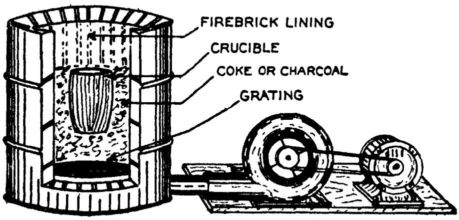
Brass and aluminum castings for the various parts of a 6″ Springfield mounting, also for brass laps, spindle parts, and various other casting needs of the amateur telescope maker, can be made at home. The job can be done at very little expense, for the cost of equipment, scrap copper and zinc or aluminum, and molding sand can easily be limited to a few dollars. The castings required for the mounting mentioned, and for some other types, do not lead the amateur far into the intricacies of the pattern-maker's and foundrymen's trades.

It is not the purpose of this chapter to attempt to give a technical treatise on casting, but to provide a starting point. The data to be given were assembled, in part, with difficulty from an experienced foundryman, though he was willing to tell all he knew, and to some extent by trial and error, as the first castings were made. Following this haphazard start I was given considerable help and encouragement in further learning the work by Lester Scheffler, chief foundryman of the government shipyard at Pascagoula, Miss., by J. L. McIlroy, machinist and foundryman, Dr. A. B. Babendreer, retired foundryman, and A. J. Watson, an electrical engineer who had foundry work in his college course, all of Biloxi, Mississippi. During the compilation of this chapter valuable suggestions and assistance were very willingly contributed by Messrs. S. H. Sheib, of Richmond, Va., W. A. Mason, of Lorrain, Ohio, Dr. D. E. Taylor, of Williamantic, Conn., Erwin H. Christman, of

Farmingdale, N. Y., and by Russell W. Porter and Arthur Henry, of Pasadena, Cal., based on their own efforts and experience with the work and with telescope construction.

Even with crude apparatus, and the first crudely applied methods in the hands of this amateur foundryman, sound and satisfactory castings were produced.

The Furnace: The gasoline drum affair pictured in Figure 1 is only one of many objects which might be converted into a brass furnace. A large cul-



All drawings by the author

FIGURE 1

vert tile, or large old stove lined with firebrick or common clay, even a hole in the ground, will answer the purpose if provision is made for a strong draft. This may be obtained from a motor blower, a hand forge blower or a stack or chimney high enough to provide the "draw." Vacuum cleaners are prevalent, and most of them can be arranged to blow and will serve well. William A. Mason and his co-builders, of Lorrain, Ohio, used one for very large aluminum castings. A 10" or 12" electric fan enclosed in a wooden packing box of suitable size, provided with a funnel of wood in front, leading to stovepipe and thence to the furnace, and with an air inlet at the back, will work nicely. The melting point of copper is about 1981° Fahrenheit, but with a good draft and coke, charcoal or oil properly arranged, plenty of heat will be developed. An arrangement which permits the use of waste crankcase oil consists of an elevated tank of about five gallons capacity, with a small feed line provided with a check valve, extended through the side of the blower pipe to the edge of the furnace. The tank should be high enough to force the oil into the furnace, or a pressure tank may be used, with about three pounds of air pressure applied. When the furnace is to be fired some oil-soaked waste is lighted and thrown in and the blower is started. Following this the oil is turned on and the furnace should be white hot within a half hour. With coke the gasoline drum affair previously described melted 33 pounds of copper in 30 minutes. The cut out top of the drum was used as a cover of the furnace when heating.

The Crucible, and Tools to Handle it: Crucibles are numbered by sizes, these being rated on a pouring capacity basis—three pounds of metal per number—and the cost ranges from 18 to 25 cents per number (1935). Thus a No. 20 crucible costing approximately $3.60 will pour 60 pounds of brass.

This is more than will be required for any one casting for the mounting mentioned, but it is well to have excess capacity. Crucibles may be ordered through local hardware merchants.

A new crucible should be treated or annealed by building an open wood fire around and over it to heat it thoroughly. Otherwise, if left unannealed, the furnace may subject one area to high heat and crack it. Crucibles are somewhat fragile and should not be handled roughly, nor should they be left partially filled with metal when not in use. Pour out any excess metal when the work is done and allow the crucible to cool evenly in the furnace and, if it would be subject to breakage in the furnace, put it elsewhere in a

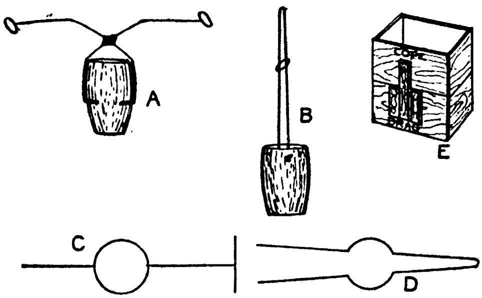


FIGURE 2

safe place when cool. Another cause of cracked crucibles is filling them with pigs of metal, improperly arranged, which expand against the sides of the crucible under heat. Care must be used to prevent this jamming. Don't put water in a crucible or allow it to become wet, as it will most probably be ruined.

Sketch *A*, Figure 2, illustrates the best tool known to me for lifting the crucible from the furnace. It may be necessary to have it made at the blacksmith's shop. Sketch *B* is a bail-like tool which may be used instead. It is operated by means of a ring which holds the ends together but which, when slid upward, permits them to be inserted into holes drilled through the crucible about 2″ below the top. The holes may be drilled with the business end of a screwdriver. The bail being thus set, the crucible is lifted by means of an iron rod or pipe run through it.

After being lifted from the furnace, the crucible is set into the ring of tool *C*, the ring having been made to fit it just below center. When pouring, the man on the T-end governs, the other merely steadying the work. Tool *D* will also accomplish the pouring, the open ends being pressed toward one another and the crucible gripped and tipped by means of them.

Cope and drag: At *E*, Figure 2, are shown the open end boxes which foundrymen term the cope and the drag. Together they are termed a two-part flask. These hold the molded sand, and are made of a size sufficient

to provide two or more inches of sand all around the mold. For the 6″ Springfield mounting, boxes for Casting I should be of 1″ × 6″ boards and 14″ × 17″ inside. For Casting II the drag should be of 1″ × 10″ boards and 12″ × 14″ inside, and the cope with the same inside measurements and of 1″ × 8″ boards. Casting III may be molded in the cope and drag used for Casting I, or in another of the same approximate dimensions. Cleats nailed

The author pouring an open mold, using the equipment described in the text. In his hand he holds the lifting and tilting tool shown in Figure 2, at B. The crucible is supported on tool C. Tool D rests against the wall. The gasoline drum furnace shows in the background. Photograph by R. W. Porter, who was present and who states that, within 20 minutes of ignition, the furnace was roaring and spitting fire like a Chinese dragon.

around the inside of the boxes will hold the sand perfectly, but with smaller sizes the rough boards usually hold the sand without other means. In larger sizes, as sketched at *A*, Figure 3, the interior space of the cope is divided into cells, and nails are driven around the inside to hold the sand firmly. The cells should be cut out sufficiently to keep them ½″ away from the pattern parts, as indicated in *B*. Handles are also provided as shown, for the weight of the sand requires the strength of more than one man. However, with the small sizes one man alone can manage them, and the handles may be dispensed with.

Guides should be provided on opposite sides, as indicated in *E*, Figure 2, and *A* and *C*, Figure 3, so that when the boxes are separated to remove pattern parts from the sand, they may be replaced precisely and the two parts of the mold caused to fit properly. The guides should be tapered as

shown, so that they will slide easily into place, and should fit snugly but slide freely.

Provision should be made to peg, latch or clamp the boxes together, as a casting may be spoiled by tipping the boxes apart, or by a separation of the mold caused by pressure of the molten metal and gases or steam. Sand, being lighter than molten brass, will float upon it. Weights are often used to hold the mold parts together. The boxes should be well nailed for sturdiness, and in the large sizes braces should be applied in the corners. If the boxes are to be dropped to knock out the sand and metal, sturdiness is a necessity. Lateral play will also disrupt the mold during handling. Cleats are some-

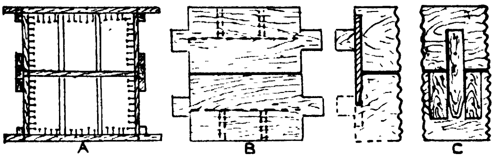


FIGURE 3

times nailed around the inside of the smaller sizes in lieu of cells or nails.

Other Equipment: Provide several flat boards to cover either end of the boxes. These are called the bottom and follow boards. Also provide a knitting needle or straight wire for venting the sand; several pieces of broom handle about 8″ long, or the equivalent; and a skimmer with a wooden handle to lift off dross or trash of any character. The latter may be dispensed with if a third man is available to hold a piece of flat metal against the lip of the crucible to prevent dross and trash from entering the mold when the pouring is in progress. A putty knife, case knife and other odds and ends may be needed to repair a slightly damaged mold. Foundrymen use repairing tools shaped like a small flattened spoon on one end, and with a flat diagonal surface on the other. An excellent substitute is suggested by W. A. Mason, this being to flatten an old spoon of the shape used for iced tea, and trim it to the required size. Bits of sand will be likely to fall into the mold, so a short length of rubber tubing is useful to blow out the loose sand. The temptation to blow out this loose sand by mouth may be irresistible, so close the eyes if this is done. Small hand bellows are used by foundrymen for this purpose.

Molding Sand: Molding sand may be obtained from any iron foundry. It is true, this is not brass sand, but it will suffice. Brass sand is finer and produces a smoother casting, but it costs more in some localities, and if expense is an item it may not be worth the difference in price, since only a small amount of work is added because of the rougher castings. By screening ordinary founder's sand through window screen one obtains a very practical brass sand. A substitute for founder's sand may be made by adding about 10 percent of clay dust to fine beach sand, the clay acting as a binder. Another substitute is to use ordinary (screened) clay dust. This will give a

very smooth casting. Fortunately some form of sand-clay mixture suitable for founder's work is found in practically every part of the country, and founder's sand is therefore not expensive. The amount of sand required will be from about a barrel up, depending on the number of castings to be made at one melt and, of course, the size of the castings.

The sand should be dampened (tempered) several days in advance of molding, so that it will not be too wet or—I hesitate to say it—too dry. W. A. Mason sets forth the foundrymens' method of testing brass sand, it being to squeeze a handful and if it is right it will retain the shape of the hand, show the lines of the hand, and the lump may be picked up and lightly handled. If it is too dry it will crumble badly. Regular founder's sand will

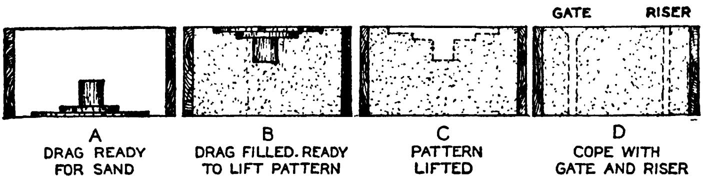


FIGURE 4

The patterns shown in this drawing and in Figure 5 are not for parts of the Springfield mounting, but are diagrammatic merely to exhibit the principles involved.

behave in the same general way, except that it will not show the lines because of its coarseness. If one must be wrong in tempering the sand it is better to lean toward dryness rather than dampness. "Green" sand, in foundrymen's parlance, means damp sand. "Dry" sand means any sand which has been dried or baked. The latter condition meets the inexperience of the amateur more than half way, as it is not nearly so exacting in skill of handling to obtain good results. Foundrymen seem to have little difficulty pouring sound castings in damp sand, but I think the best insurance the amateur can provide against spoiled castings (blow holes, gas pocketing, scabbing, etc.) is to dry the molds, either by letting them dry a week or more, or by drying them in the kitchen stove, if one has metal boxes such as the foundrymen use in small sizes. For aluminum castings this may not apply, but with brass, melting at 600° to 700° higher temperature, and the probability that the sand will not be as dry in the amateur's hands or as well handled and vented, the chances of success will be greater with drying. By drying the mold the action of gas and steam is greatly diminished, improper tamping is taken care of, and the porous quality of the sand will usually take care of the gas and steam which must leave the mold before the metal solidifies.

Molding: Place one of the flat boards on a bench, and on it place the bottom box (drag), inverted. In the center of the box and on the board place your pattern, or part of pattern and, if you like, indicate on the edges of the box where the pattern rests. Sketch *A,* Figure 4, shows this first operation. Sift molding sand through window screening around the pattern,

tamping it carefully into its corners. The screened sand acts as a smooth facing for the mold. Continue until the pattern is covered, and then tamp the box full from this point with unscreened sand. Heap up the sand a bit, scrape off the excess with a straightedge and pat the surface smooth with the hands. Then take the straight wire or knitting needle and vent the sand by pushing it down through the sand all around the pattern, about ½″ away by guess (this is the purpose of the marks), also through almost to the top of the pattern, in each square inch, or less, of sand surface which shows. Sometimes it is better to cut channels across the surface of the sand about 1½″ apart and vent in a line with these, so that the gas may escape to the edge of the flask. These holes allow gases and steam to escape from the mold without blowing it apart, and prevent spoiling the casting by pocketing.

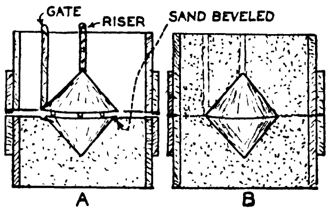


FIGURE 5

Now place another flat board on the box and, while holding both boards in place, roll the drag over, lift off the board, which is now on top, and the pattern is exposed to view in the sand. With a complete pattern, such as the one sketched in *B,* Figure 4, the next step is to draw it from the sand. Set a screw in either end or side of it and loosen it by tapping sidewise in varied directions. Draw it out by means of the screws, slowly and carefully in order not to disturb the mold. Slight damage to the mold, caused by this operation, may be repaired with the putty knife, teaspoon and other odds and ends. A few drops of water at the place to be repaired will assist. It will be helpful to brush the sand around the pattern with water before drawing the pattern.

With the drag now ready, as shown in sketch *C,* the top box (cope) is next prepared for a flat surface of sand with the pouring (sprue, gate or ingate) and riser holes—note sketch *D.* The top box is placed right side up on a flat board, and sections of broom handle are held in positions approximating opposite sides or ends of the mold. Sand is filled in and tamped around them in the manner described above, and likewise vented thoroughly. The broom handle sections are then loosened and drawn, and the cope is turned on its side for drying. The one part pattern has now been molded.

Usually, however, it is not possible to form a pattern in such a way that it will be complete in the drag, and it must be divided into parts, in order that it may be drawn from the sand. Both drag and cope hold parts of the two piece pattern, as shown in *A,* Figure 5, the double cone being used to

represent an example of such a pattern, since it will readily be seen that no means may be provided to remove it from the sand except to split it on the plane shown, or on a longitudinal plane from point to point. The procedure of molding a two-piece pattern is the same until the drag is turned right side up, except that the lower half of the pattern is not then removed from the sand. Instead, the other half is placed on the lower part and the cope is fitted into place. The surface of the sand in the drag is dusted with parting sand, in order to prevent the sand which will now be put into the cope from sticking to the sand in the drag. Parting sand may be obtained from a foundry. Lycopodium, a vegetable spore, seems to be the fundamental part of the best parting sands (really flour-like powder). "Partina" is the trade

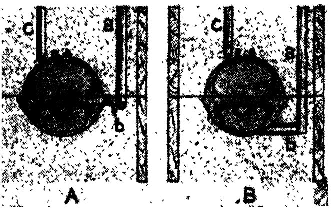


FIGURE 6

name of another one, very similar. If it is not possible to secure one of these, dust, talc, powdered mica, or dry beach sand may be substituted. Burned brass sand is also effective for parting. It is essential that any of the substitutes which is used be thoroughly dry, so that at least a time will elapse before moisture can be absorbed from the molding sand to cement the two surfaces together. The foundry varieties do not absorb moisture, and hence they provide a perfect means of parting.

A section of broom handle is set at one side, as shown in Figure 5, for the pouring hole, and sand is sifted into the cope and tamped. The molder should take care not to drive the sand in the two boxes together, but should tamp lightly at first. Continue until the box is filled high enough to set the section of broom handle for the riser, thence on until the cope is filled. Vent in the usual manner. The broom handle sections are loosened and drawn, and the cope is lifted slowly and carefully from the drag, without any jerking or jarring motions, and is set upside down on the bench. One part of the pattern will show in either box. Before the parts are drawn, press down the edges of the sand a little around the pattern, so that the sand will not break off or bulge when the cope is again replaced, and swab the edges with a little water. The pattern parts are then drawn and the two-part mold is complete. Two-part patterns having core prints mold in the same manner, and the cores are made to form and inserted before the cope and drag are fitted together again.

Some thought is suggested when placing the gate and riser, so that the resulting shafts of metal may be cut off of the casting without difficulty. With some patterns it is better to place the gate at the side and ditch to the mold, as shown in *A*, Figure 6, *a* being the broom handle, *b* the ditch and *c* the riser section. With others it is better as shown in *B*. In this case *b* is a hollow core section leading to the mold. When a mold has light partitions of sand which will "wash," as with gear teeth, it is better to gate from the bottom, and this is accomplished with a horn-like section of wood leading from the bottom of the mold to the top surface of the sand in the drag. From this point the broom handle section takes care of the hole through the cope. Also, in the event that the mold has a light partition of sand through the middle, ditches from the gate should lead to both sides so that the weight of metal will not push the sand aside.

In brass founding, the riser should be as large as the gate. When the metal is poured into the mold the best of it stays in the bottom part, and if the riser is small and short the top part of the casting may prove unsound. Its height should be at least 4″. The unsound tip of the shaft of metal in the riser and gate is sometimes termed the "deadhead."

How hard to pack the sand is not as important with "dry" sand as with "green" sand. Part of the foundrymens' skill is in the tamping, yet no two foundrymen tamp the sand alike. One of the principal reasons for suggesting the "dry" sand method is to get around a lack of skill. Foundry sands also differ in silica and alumina content, and some compositions will not stand as much drying as others, becoming dust when the metal is poured. The first casting will indicate how the sand will act. Molds may also be "skin dried," that is, not completely dried all the way through but the outer surface fairly dry. Speaking as one amateur to another, you may succeed without drying the molds at all, if the tamping and venting are properly done—the venting should always be—but if you do try damp molds, you run the risk of hot metal scattering about a bit from blowing, beside the greater chances of having to do the work over again. I have been told that large bells are cast in clay molds which have been baked hard, in order to obtain the soundness of metal which provides the tone. Benvenuto Cellini (1500–1571) used clay for the molds of his statutes, and baked them several days before pouring the bronze. A description of his methods is contained in his autobiography.

Core material may be composed of ordinary sand dampened with linseed oil—just enough of the latter, more or less, to discolor the sand. There are many formulas for core materials but the one mentioned is recommended by Scheffler because it is simply composed, bakes well, and then the oxidized linseed oil binder disintegrates under the heat of the brass and the remainder may be easily removed from the interior of the casting. Any formula used should have this latter characteristic. The National Bureau of Standards, in Letter-Circular 252, gives formulas and details of handling rubber and balata

binder cores which do not require baking,* need not be vented and do not stick to the core box.

After a core box is filled with material and ready for the flat iron sheet on which it is to be inverted it is a good idea to secure two or three sheets of heavy, casein-sized magazine paper and place them over the core box. This will bring the paper under the core when inverted on the iron and will prevent it from sticking to the iron.

Cores may be baked in the kitchen oven (if the family is away from home or is tolerantly minded). The time required for baking depends on the thickness of the material to be baked, but with the oven at a moderate heat (about 400° F.) 1″, roughly, will bake per hour. This will give an idea of the time required for any particular job.

Cores made in halves may be pasted together with ordinary flour paste.

Cores must be vented. The cylindrical ones made in halves and pasted together may be vented by cutting a channel through the center and extending this channel through the sand to the edge of the flask. Those not so made must be vented in the core box. The vent or vents should be quite large, at least ½″ on the larger sizes, ¼″ on the smaller. Stoppage in the vent channel sometimes spoils a casting.

Pouring the Metal: When the furnace is fired with coke or charcoal a bushel or more is placed under the crucible, and the space around it filled with the same fuel. Copper is weighed and placed in it, and an old clay jar cover or a regular crucible cover is placed over it. Coke gives off gases which will be absorbed by the metal to its detriment, unless these are kept away from it. If you do not wish to be scientific, you may arrive at the total volume of alloy needed by guess, from the looks of your pattern. A guess for plenty is advised. The method commonly used by foundrymen is to weigh the pattern and multiply this weight by 15, then add 25 percent to the result and divide this final figure into the respective proportions of copper and zinc. This applies to patterns of fir, pine, cypress and mahogany, and to a final alloy of brass or bronze. Core prints should be allowed for in making this computation.

When the copper is melted, the zinc, also weighed, is added, and this will melt almost immediately. The alloy is then stirred a minute or two with an iron rod, in order to mix the metals thoroughly. If the bail-like tool is used to lift the crucible it should be inserted before adding the zinc, as the high temperature transforms part of the zinc into smoke and fumes, and poor vision and the heat may make the job difficult. If the metal seems fairly liquid the pouring may be done at once, but one test of the proper temperature is a white feathery condition at the edges of the metal in the crucible. To a beginner this is somewhat beside the point—just be sure the metal is in

* In a letter the author, whom it seems tried to bake the cores in the home kitchen range, makes the following statement. "That acrid smell from burning linseed oil makes the old man as welcome as a skunk at a garden party. Maybe the above, if included, will save some family fights at some time in the future." It is hereby included, with apology to Dorothy Dix, on the ground that it is "practical" information.—*Ed.*

condition to pour freely. The crucible is then lifted from the furnace and set into the pouring tool, which should be ready to receive it. Skim off the dross and trash, or have a man hold the flat metal against the lip of the crucible, and pour continuously until the riser is filled.

I was told to throw a handful of charcoal dust into the crucible as soon as the copper is melted, in order to prevent and reduce oxidation of parts of the alloy. Copper phosphate for brass, and tin phosphate for bronze, are sometimes used for the same purpose. I was also told to throw a handful of sand over each hole as soon as the metal is in the mold, to prevent too quick cooling of that part of the casting and to maintain heat in the metal until the gas generated has time to leave the mold.

All metals which are to be alloyed should be melted in order of their melting points, from the highest to the lowest. It is best to melt the metals as quickly as possible, that is, not to allow the melting to drag over a long period, as oxidation goes on steadily. After the metal is poured it should be allowed to stay in the sand for a half hour or more, as sudden cooling of a hot casting may warp it disastrously.

Brasses, Bronzes and Miscellaneous: While there are many formulas for brasses and bronzes, it seems best for us the amateurs to stick to the simple and inexpensive one of 60 percent copper and 40 percent zinc, sometimes called Muntz metal, which Dr. S. H. Sheib, amateur telescope maker, chemist and testing engineer, of Richmond, Va., uses and recommends as the best for appearance, strength and workability for telescope purposes. This alloy seems to be easier to handle from a standpoint of uniformity of color in the various castings, since the amateur is unlikely to have a furnace or crucible large enough to pour all castings from the same melt, and the color variation in some of the brasses and bronzes in the amateur s hands may prove noticeable. Dr. Sheib also mentions that lead will not alloy with copper unless deceived into doing so by adding enough tin or zinc, both of which are friendly to lead and to copper.

The use of scrap brass or scrap bronze prevents knowing the real composition of the final alloy, and is unsatisfactory from a standpoint of predetermining the color. It is also unsatisfactory in that, if the scrap is not of good quality, the casting may be unsound. However, if scrap of this character is used, additional zinc or tin should be added before pouring, for these burn out and the resulting composition is often sluggish and difficult to manage.

My first castings were composed of bronze, because the formula, 85 percent copper and 5 percent each of tin, lead and zinc, sounded pleasant and had everything in it except, perhaps, the kitchen stove. Dr. Sheib's recommendation seems the best from all standpoints for the beginner.

Graphite flour and charcoal dust are often shaken through a cheesecloth bag into a mold to provide a smoother casting. Molds are often "sleeked" with these by troweling them smoothly over the surfaces where possible.

Some arguments are in order on the relative merits of brass, bronze or aluminum for the mounting. Aluminum is easier to handle, because of the

lower temperature. Some claim that brass—plain old yellow brass—nicely machined, looks the best and I join this side. Use the one you want, or all three of them. Some might even prefer silver, gold—or platinum.

If arrangements for the draft can be provided without cost, the remaining expense for castings for the 6″ Springfield mounting should not exceed $5.00. The exact sum depends on the availability of scrap copper and zinc or aluminum and the cost put into the other tools mentioned, and on the foraging or borrowing abilities of the man. In a telescope makers' club the whole matter would be greatly simplified.

Good luck to any who try.—*404 Reynoir Street.*

The author, with a small casting.

Molding and Casting a Fork

By WILLIAM A. MASON
Lorain, Ohio

[EDITOR'S NOTE: The telescope shown in Figure 1 is a 12½" Cassegrainian made by the author, assisted by John and Jim Cloughessy and Dick Curran—the latter a molder—and progress photographs which are shown on these pages tell much in themselves regarding this kind of job. Before presenting the

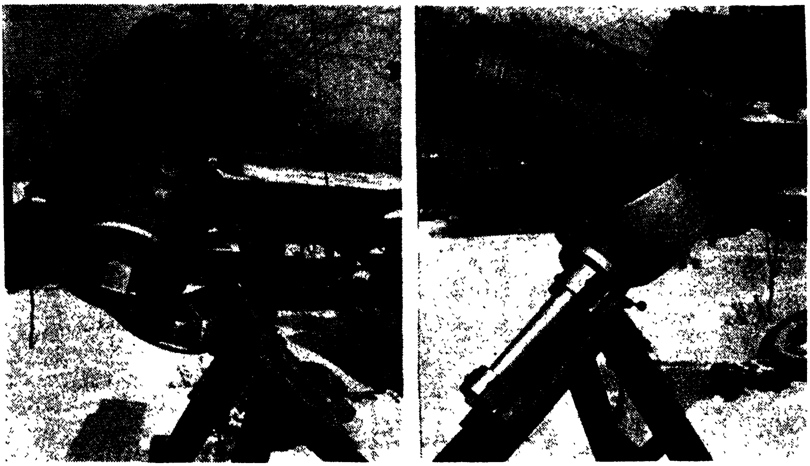


FIGURE 1

series, with the author's running comments on them, a description of the telescope itself will be of interest. The castings are all of aluminum and they account for 125 of the 180 pounds total weight of the telescope. The 12½" primary is of Pyrex, with 39" focal length, and the secondary is 3¾", also of Pyrex good to one tenth of a wave. The eyepiece holder is on a sort of swivel, so that it may be swung around at any angle, and will take anything up to 2" O.D. eyepieces. The lower half of the telescope tube screws off the trunnion ring, and contains the cell. There are worm-driven slow motions in Dec. and R.A., and the drive is by a governor-controlled induction motor. Two of these telescopes, practically alike, were made. The tapered axes are interesting.]

The left-hand picture in Figure 2 shows Dick Curran, molder, who assisted on the casting work, also the drag turned right side up. As stated previously by Ferson, the drag is first placed upside down on a large flat square board, with one half of the pattern—the half which has no dowel pins—placed inside it. Sand is tamped round the pattern until the drag is full, and then

leveled off by scraping with a straightedge. Another large flat square board is then placed on it and the whole thing—drag and the two boards—is turned over, the top board being then removed. The picture shows the other half of the pattern in place exactly on the first half, and Curran is holding up the cope to show its cellular structure. The wood is cut away wherever necessary, to clear the pattern. Large nails [only dimly visible in the reproduction.—*Ed.*] project inward to hold the sand. Note light-colored parting sand on the drag.

The right-hand picture shows the cope being "rammed up." Note the guide for the cope and drag, in front, also the handles. Fine sand was sifted

FIGURE 2

("riddled") to cover the pattern and make it smoother, and the cope then filled with unsifted sand. Before filling, however, a piece of pipe or round stick about $1\frac{1}{2}''$ in diameter was put in, to form the gate. We leveled the sand around the "gate pipe" for a few inches, so that an extension could be placed on top after the cope was back in place, to make the gate higher [comment by Porter: "Good"]. A piece of 6" stovepipe about 6" or 8" long, filled with sand and having a hole through the center to match the gate, is good. Make a funnel shape to the sand in the end of it, to help in pouring.

In Figure 3 the left-hand picture shows the drag and cope after the cope has been lifted and placed on edge. The molder is chamfering the sand around the pattern by packing it with a trowel—he was until I took the picture! This job is to be done on both the drag and cope. Not very deep—about $\frac{1}{16}''$ on each. This helps prevent the sand in the cope and drag from being forced together too tightly at this point, and some of it being pushed inward and causing a hollow in the casting. It is better instead to have a

small fin on the casting. The gate—light spot—may be seen in the middle of the cope. Ditches in the drag, to carry the metal from gate to cavity, also show. When lifting the cope, be careful not to lift one corner or side faster than any other. Stand the cope on edge and then tip it back as far as necessary to remove the pattern and repair any damage to the sand. Try not to bump or distort it. For this particular job lifting the cope required two men (preferably more), as it weighed over 150 pounds.

The right-hand picture is about the same as the other, but the other half of the pattern has been removed from the cope. Some small bright dots

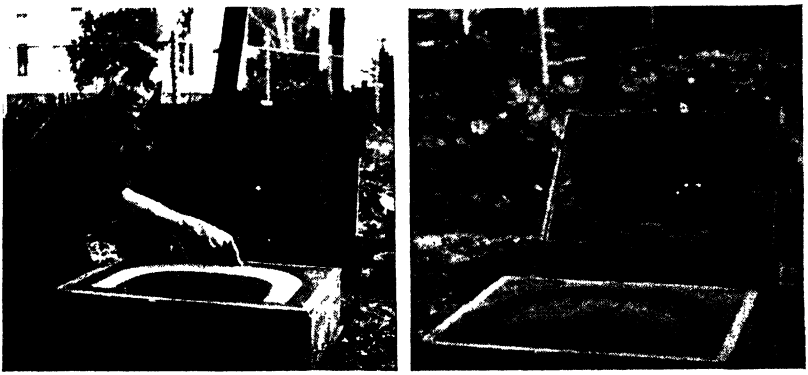


FIGURE 3

are visible near the edge of the depression in the cope. These are nail heads, the nails having been put in to hold some sand which didn't stick very well. Note that no ditches were put in the sand of the cope. It is not necessary to provide these in both cope and drag; also, the less the sand is disturbed in the cope, the less the likelihood of sand falling.

In Figure 4, the left-hand picture shows Curran with a large nail in position to push in at a place where sand is likely to fall off. Sometimes nails may be put in when putting in the sand, but there is then a chance of hitting them with the ram, which would tend to loosen the sand or cause a crack in it. When ready to put the cope back on the drag, use the same or more care as in lifting it off. It will be well to have a man watch the under side of the cope as it is being lowered into the drag, as long as it can be seen, in order to see whether any sand falls off. There is no use of pouring a job if the mold is no good.

Be sure the aluminum is hot. It should be fairly bright red when something is held over the pot to shade it if outside in daylight. Pour without any hesitation until metal runs out of the risers [comment by Ferson: "Right—if you stop, there is Hell to pay"]. Wearing goggles is a good idea. Leave a casting of this size—50 pounds—in the sand at least half

an hour, while an hour will be better. Leaving the oxide that forms on the aluminum until ready to pour may be well, as aluminum oxidizes very fast when hot. Proof of this is the speed with which oxygen leaves iron oxide and combines with aluminum, with the production of much heat, in Thermit welding.

The right-hand picture shows the result, but this is not the casting as it came out of the mold, for the trunion bearing caps have been cast and fitted on, and holes drilled for a boring bar. There were several "shrinks" in the casting. Shrinks are hollows, formed in thick places where the metal sets a little slower than in the thinner places. Where the metal sets first, some of the shrinkage is made up by metal flowing from adjacent places which are heavier and don't set quite so quickly, leaving a hollow place. [Comment by

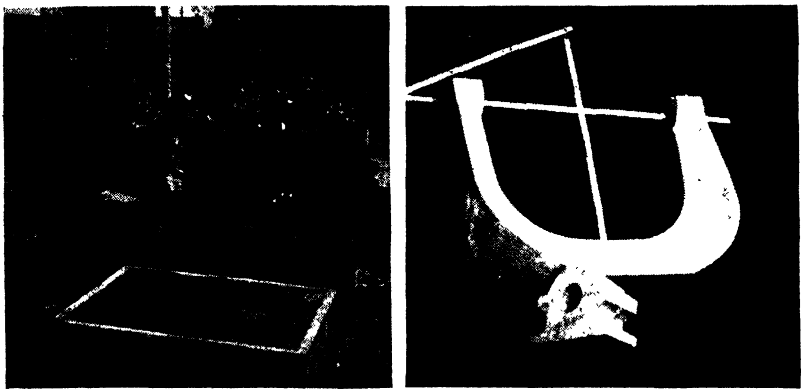


FIGURE 4

Porter: "If possible, in pattern making, design so that there are no thick places to shrink."] This is sometimes prevented in foundries, I have been told, by "chills"—pieces of steel placed in the mold at thick places, to chill the molten metal there a little quicker. Probably better design of the fork and pattern would also prevent some of the shrinks, but sometimes a fellow can't very well make the patterns as he would like them, for lack of money or equipment.

[R. W. Porter: "There should be a note somewhere stating that the cleanest—best—part of the casting is at the bottom, and the pattern so made that, if there is any preference with regard to having one part of the casting better—more uniform—than another, such as where tracks come or machining is done, this part of the pattern should be *down*."]

Machining the Springfield Mounting

By Russell W. Porter

Snag all castings with chisel, emery wheel, or coarse file, to remove burrs, fins, sand and rough spots. Refer now to Figure 1, *a*.

The saddle, I, requires no machining more than tapping the four holes for the push screws and filing the bosses against which the circular plate is screwed. The circular track plate is machined either by bolting it to the face plate of the lathe or pressing it on to a taper arbor. Carefully finish the edge to be graduated for the Dec. circle. If the lathe gears make it possible, graduate to single degrees before removing from the lathe. If not, resort to the method described on page 39, "A.T.M.," by using a band with the degrees numbered as indicated at *b*, Figure 1*a* (lower left-hand corner of the page).

Casting II is really a milling machine job, but one way to machine the right angle faces and central holes would be to bolt the casting to an angle plate secured to the face plate of the lathe. But there is scarcely enough room on a 13″ lathe to do this, so I sent a set of castings to C. C. Chapman of Riverside, California, one of a live group of amateurs in that city, asking him to use his own ingenuity in machining them, but not to go beyond a lathe of 13″ swing. It developed that he followed the steps shown in Figure 2. The description of the operations is as follows: At *A*, clamp to drill press table and thread ½″ hole. Face off boss at *a*. At *B*, screw out to stub chuck mandrel *a*, and face off *b*. Scratch lines at *c*, *c*. At *C*, center drill at *c*, *c*, mount on centers and face off *a*. Drive with dog. At *D*, mount in independent jaw chuck, as shown, and bore out hole *a*. The interesting step here is that the facing operation at *C* is on centers eccentrically located from the hole bored out in *D*, the sole purpose being to face the Dec. track truly square with the R.A. track. Finally, II may be pressed on to a mandrel and the edge *b* machined. This edge, as shown in Figure 1*a* of the present chapter, also in Figure 3 of the opening chapter, will form seats for the Dec. index and Dec. slow motion unit.

Casting III is treated very much like I. Drill and thread the three holes for the adjusting screws, file down all bosses, and screw on the circular track plate.

There remains the worm wheel, the hobbing of which can be done on the lathe, by means of a tap (see Figure 3), a worm then being cut on the lathe to duplicate the tap. The wheel blank is first machined all over, according to the working drawings in Figure 1*a*, and then mounted on the stud fastened to the tool post carriage (See Figure 3). The tap is mounted as there shown. It automatically rotates the wheel, and if every tenth tooth is carefully laid off and scratched on the rim of the wheel, the cutting progress may be watched to see that the teeth generated are not creeping ahead or lagging behind the intervals marked on the rim. It will require considerable force to accelerate or retard the wheel, in overcoming the rotation created by the

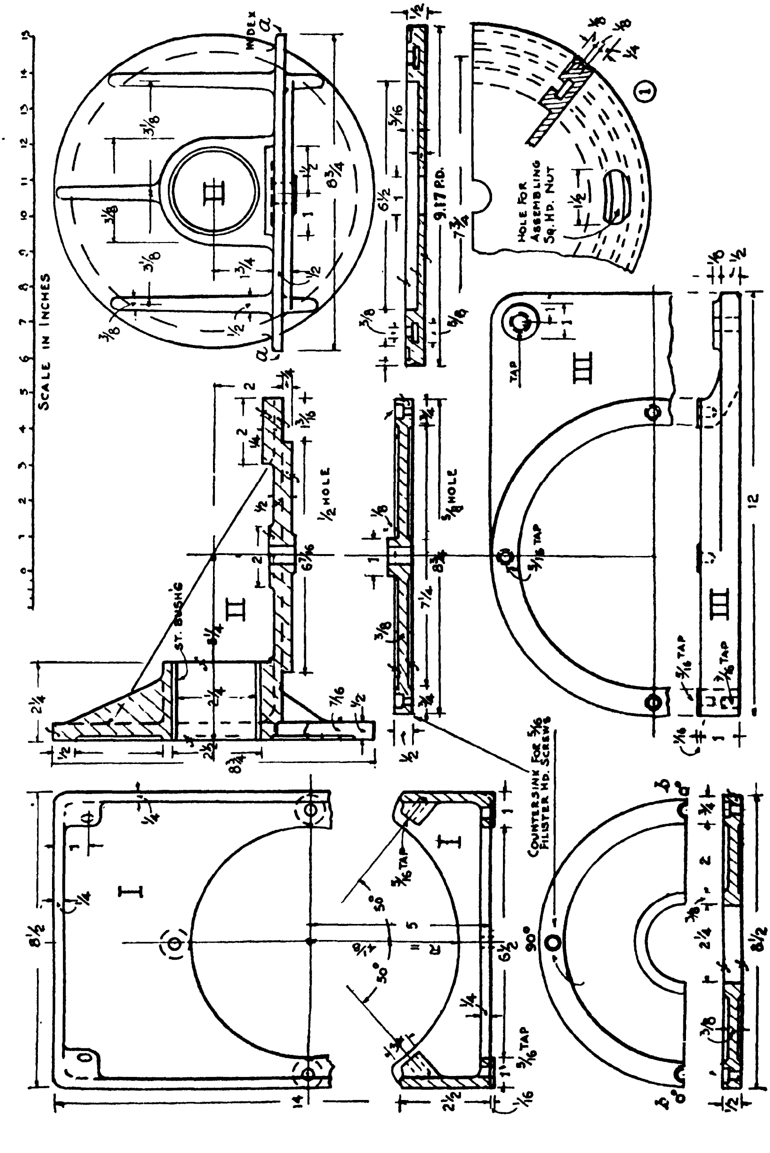

SCALE IN INCHES
INDEX
9.17 P.D.
HOLE FOR ASSEMBLING SQ. HD. NUT
TAP
ST. BUSH'G
1/2 HOLE
5/8 HOLE
COUNTERSINK FOR 5/16 FILISTER HD. SCREWS

FIGURE 1a

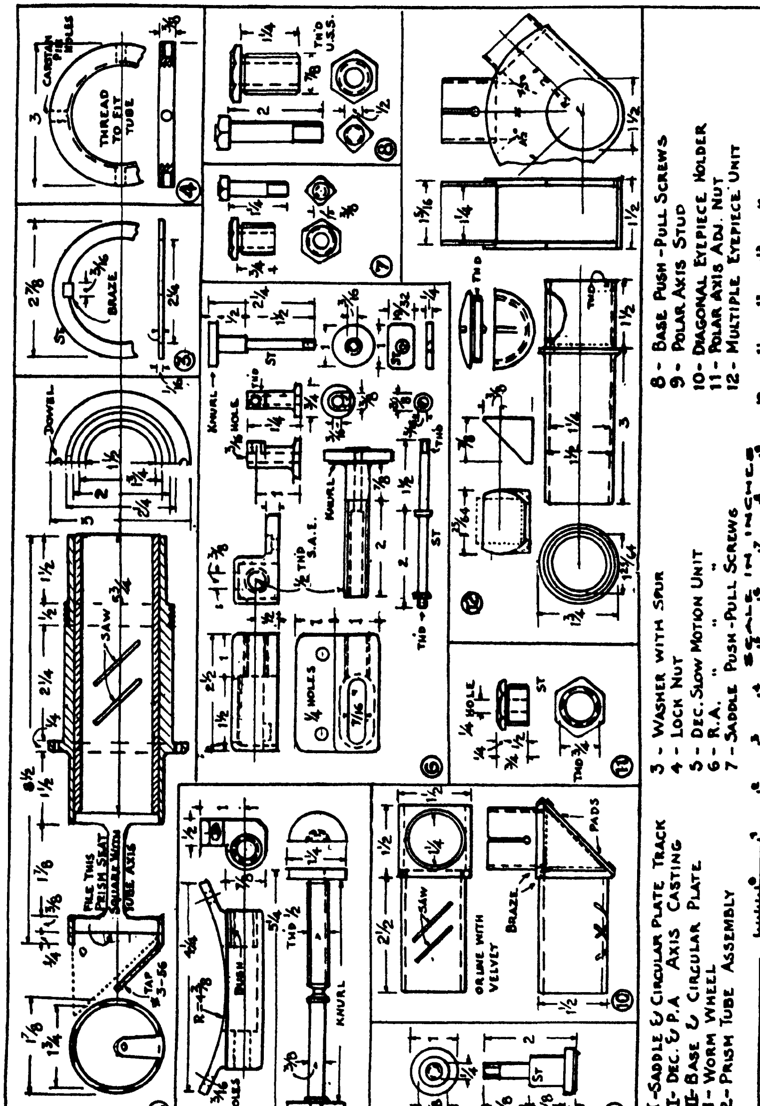

I-Saddle & Circular Plate Track
II- Dec. & P.A Axis Casting
III- Base & Circular Plate
1- Worm Wheel
2- Prism Tube Assembly
3 - Washer with Spur
4 - Lock Nut
5 - Dec. Slow Motion Unit
6 - R.A. " "
7 - Saddle Push-Pull Screws
8 - Base Push-Pull Screws
9 - Polar Axis Stud
10 - Diagonal Eyepiece Holder
11 - Polar Axis Adj. Nut
12 - Multiple Eyepiece Unit
Scale in inches

FIGURE 1b

tap. The smooth cutting of the tap is greatly aided by providing a support under the wheel and as close to the tap as possible.

The number of teeth in the wheel and its pitch diameter are considered under the later chapter on Motor Drives. It is not necessary to groove the edge of the wheel before hobbing it but, if you do, make its radius a little larger than that of the tap.

The remaining parts of the mounting are fully covered in the working drawings of Figure 1*a* and 1*b*. If the castings are of aluminum the hollow Dec. stud of II should be bushed with steel. The castings may all be of

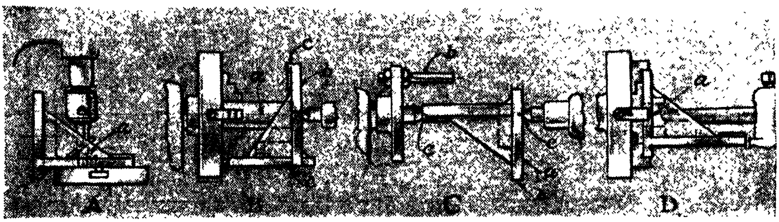


FIGURE 2

aluminum, cast iron or brass, as also the worm wheel itself. The worm and wheel, should, of course, be of different metals.

Miscellaneous: Hard wood mandrels are not to be sneezed at, and may be used in machining tubes 19, 20, 21, Figure 3, opening chapter. The mandrels are made by screwing lag screws to the ends of the wood and center-drilling their heads; then turning them to required diameters. The tubes are first chucked and supported on the steady rest, and the insides bored to size. Then they are slipped on their mandrels and the outsides finished. Brass piping may be used for these tubes, if the right sizes are available. Pipe walls are 1/8" thick. Hardware dealers can order for you almost any size tubing, in any length desired.

Before the two bands 26, Figure 3, opening chapter, encircling the telescope tube, are riveted to the tube, saw them through, as at 27. This will insure a tighter fit to the tube.

Don't skimp on the gage of the telescope tubing—18 gage is none too heavy.

To cut off stray light from the inner walls of 19, 20, 21, same illustration, cut the finest possible thread on all their inner exposed walls. When given a dull black finish there will be no internal reflections.

Going back now to the model shown at *A*, Figure 1 of the opening chapter, this mounting differs from *B* only in webbing the middle casting II. This casting was the part selected as an example in the chapter on pattern making, as it offered a good chance to explain the ins and outs of core boxes. No machine drawing is necessary.

Finally, there may be some who cannot, or do not want to, bother with

castings at all, let alone making patterns. By sacrificing only the esthetic "stream lines" of *A*, Figure 1, opening chapter, which only cored castings can give, an alternative will now be described and illustrated in Figure 4. The idea is to clamp the two tracks of II to a 6″ length of 6″ × 6″ commercial steel angle, *O*, Figure 4. Of course, II is, as already stated, a milling machine job, but you can get away with it on a lathe, provided you have an accurate angle plate, *A*.

Since the approach to 90° of the two tracks of II will be no better than the angle plate itself, this plate should be a good one. The following steps

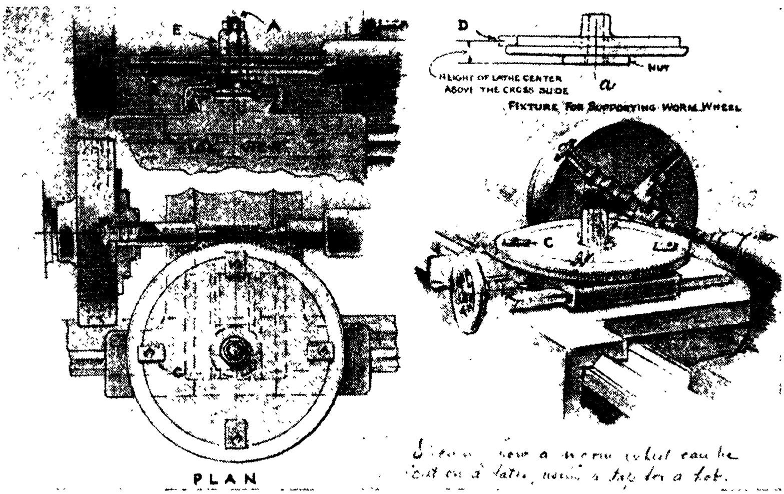


FIGURE 3

are fairly obvious, as shown in the sketch. Face off one side of the angle, turn it over and face off the other.

There are three circular plates 1, 2, 3, each about ½″ thick, 8″ diameter, with identical tracks, to be machined and bored while bolted to the lathe angle plate. If studs are driven on to the tapered hole of the lathe headstock spindle, or a stub chuck mandrel is turned up for the central holes of the plates (previously drilled and reamed) the tracks and surfaces to receive the graduations will be held concentric.

Two of these plates are screwed to the angle plate making II. The third is screwed to 4, forming I. Wooden saddle blocks 7, 7, are added, and the tube attached as shown. Plate 5 has its track machined on itself, and 6 is permanently fastened to the pier at the proper inclination to the southern horizon (90° minus the latitude of the place). Three adjusting screws are added. The hollow stud 9 is screwed and doweled securely to plate 3.

Otherwise the mounting follows the details given in "A.T.M.," page 30 *et seq.*

There is an improvement on the above. If a 7- or 8" angle is obtainable, plates 1 and 2 can be eliminated entirely by machining the tracks directly on the angle. The angle is shown at 10, attached to the angle plate. Corners at 11 are removed with a hack saw and filed smooth. Still, I don't like the

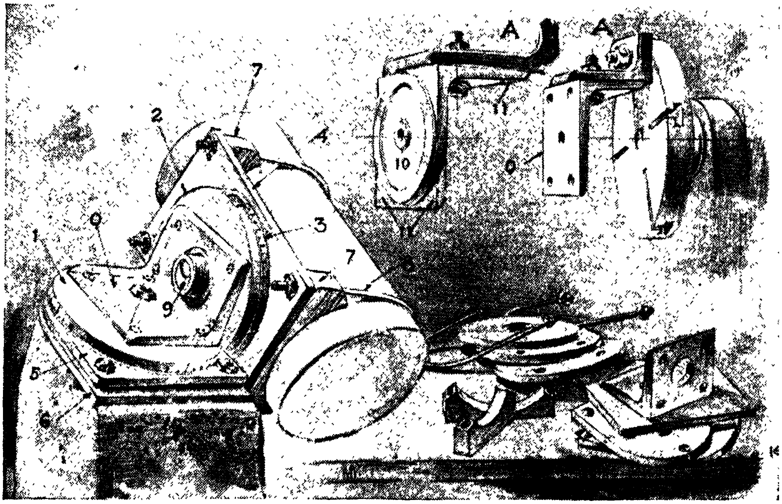


FIGURE 4

looks of that heterogeneous mess in the lower right corner of the sketch, ready to be assembled—there are altogether too many parts.

To sum up: I have redesigned the Springfield mounting with the following objects in view:

1st—To enable those who desire to make their entire mounting, to use patterns that require no coring, and to do all machining on a drill press and a 13" lathe.

2nd—To provide either hand or motor drive.

3rd—To incorporate a star clock—the slip ring—as an integral part of the mounting, in such a way that it is available throughout the evening for star settings in R.A.; to provide a slow motion hand control in R.A., independent of the clock drive; and to retain the maximum of rigidity consistent with a mounting of this type, also to eliminate any chances of back lash.

Motor Drives, Counterweighting, Pier—Springfield Mounting

By Russell W. Porter

The telescope, in order to follow the stars, makes one complete revolution in a sidereal day (See Lower's chapter on drives). This interval of time is about 4 minutes shorter than 24 hours. Several prime movers are available to the amateur—a falling weight, coiled springs from obsolete phonograph boxes, the synchronous motor.

The first two of these require adjustable governors to control the escapement, but the synchronous motor, taking its power from the readily obtain-

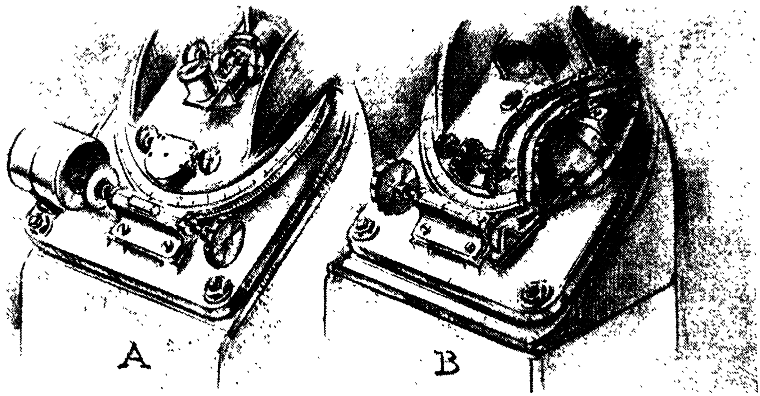


Figure 1

able lighting circuit, has the advantage of a uniform rate of rotation given to it by the relatively constant frequency of the lighting circuit. This property very much simplifies the driving mechanism, and as synchronous motors are now on the market at reasonable prices, I have chosen this kind of drive as being on the whole the most convenient for the Springfield mounting. Synchronous motors in small house clocks have reductions already in them, with a pinion shaft at 1 r.p.m. (minute hand). Their wattage is hardly enough for a large telescope, but they have been used satisfactorily on 6″ mountings.

Figure 1, at *A,* shows the motor attached to the mounting—outside, where it is easily accessible, and where it also relieves the amateur of the necessity of making an extra base-box casting, which would require a cored pattern, as in *B.* If a synchronous clock motor is used, as previously referred to, a 5-to-1 reduction by means of spur gears will give the main worm 1/5 r.p.m. Then, in order to turn the polar axis shaft once a day, 288 teeth are cut in a worm wheel of 9.17″ pitch diameter, with a ¾—10-pitch tap.

For a more powerful drive, one of the Barber Coleman motors (Barber Coleman Co., Rockford, Ill.) will answer. They come with various gear reductions from 30 to 2 r.p.m. Using the slowest, 2 r.p.m. and an additional 5-to-1 reduction, the worm wheel will have 576 teeth and a pitch diameter of 9.17", and be hobbed with a ¼—20-pitch tap.

These motors are of 10 watt capacity and cost about $8.50 (1935). This includes the reductions described, a dust cover, and a frame for attaching to

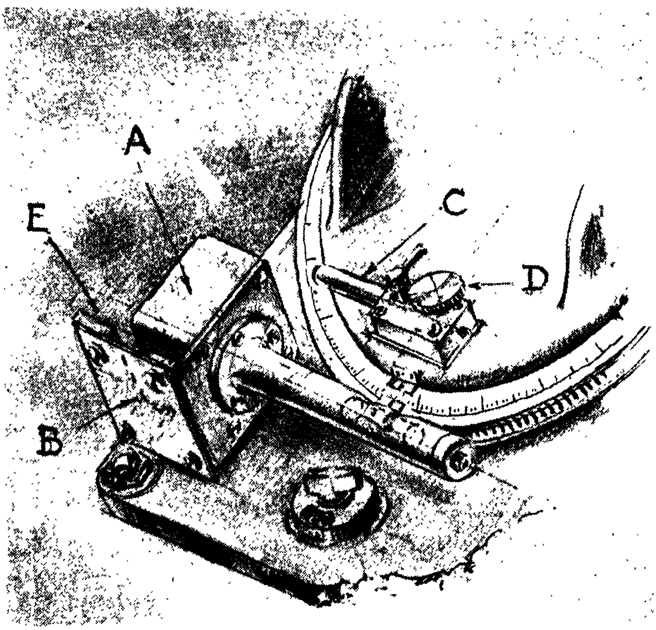


FIGURE 2

the base casting. The motor without the reductions is $2.40, (1935) but the saving in cost to the amateur, after he had bought and assembled the necessary gears, would be negligible.

The armatures of these synchronous motors have a fairly high r.p.m.—2000 for 50-cycle current and 2400 for 60-cycle. When it is recalled that a sidereal day has 1436 minutes in it, then the actual reduction from the rotor to the polar axis shaft of the telescope mounting is seen to be well over three million. $1436 \times 2400 = 3,446,400$. No wonder, then, that these tiny motors will take care of all friction losses due to worm and gear reductions and weight of the telescope, and still deliver a surplus of power for any size

telescope an amateur is likely to build. Remember that the motor should be placed at the right or left of the worm, so as to turn the polar axis shaft clockwise, looking down the axis. A hand wheel may be added at the other end of the worm wheel shaft, for a hand drive when the motor is out of commission. Of course, provision must be made for releasing the motor when the hand drive is used. But don't forget that this hand control will soon render the R.A. setting circle inoperative as a sidereal time keeper.

Figure 2 is a schematic representation of a clever and highly practical device for taking the backlash out of the main worm and wheel. It is due, so far as I know, to Chapman, of Riverside, California. Several amateurs

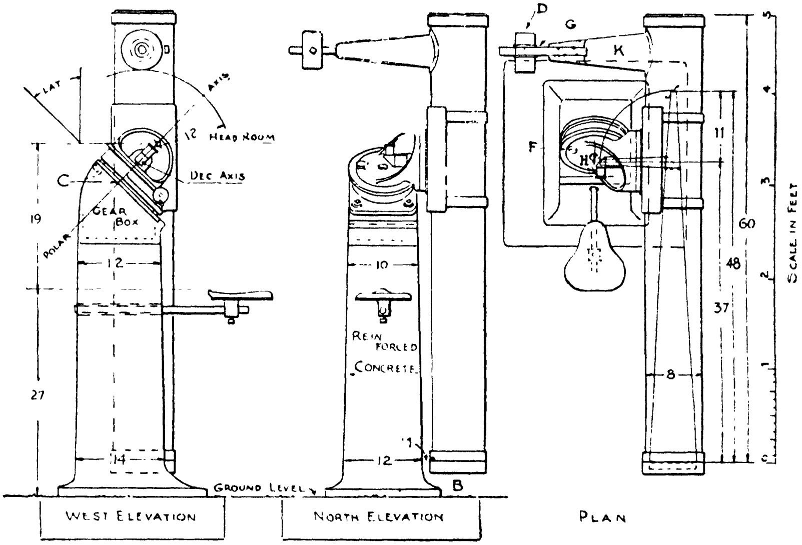


FIGURE 3

in southern California have adopted the idea. It consists of mounting the entire motor and worm unit on a membrane *B*, made of thin flexible metal, such as spring bronze. The pedestal *E* can be so adjusted on the base casting as to flex the membrane sufficiently to assure ample pressure of the worm against the wheel. The worm should be properly adjusted to mesh with the teeth of the wheel, by making the screw holes in the membrane slightly oversize. Really this membrane support for the main worm is a godsend for removing all looseness and consequent backlash due to wear, and providing a constant pressure.

I have failed to detect any vibration in the telescope, due to the motor being mounted on the base. By placing my teeth on the dust cover I can hear by bone conduction (I am quite deaf) the rotor, but feel no vibration.

There are several ways of moving the telescope in R.A. and still keeping sidereal time. However, I have tried to keep in mind the fellow with meager equipment and remote from supplies, but with enough enthusiasm and resourcefulness to grasp the ideas involved, and then left him to use his own judgment and ingenuity in his choice of methods.

Counterweighting: With both Dec. axis and telescope tube horizontal (Figure 3, plan) the balance about this axis is first determined by adding sufficient weight *D* on rod *G*. Then free the R.A. clutch (slow motion stud *F*) and adjust the balance about the polar axis by moving this weight along rod *G*. This may require several repetitions but, in the end, when the tube remains free and stationary in all positions, the concentrated load will be at *H*, the crossing of the two axes of revolution. In this state of equilibrium, and recalling the reference to adjusting the weight on the polar axis stud *I* of Figure 3 of the opening chapter, but little power will be needed to drive in R. A.

It will be well, however, to cast an eccentric hole in this weight *D*. One way is to cast the weight about a tube that will slide over rod *G*. First chuck a tin coffee can (give it a ½″ eccentricity) and bore out a hole in the bottom of the can that will just receive the tube. Drive the tube into the ground, slip on the can, line up the tube with the can and pour the lead. When cold, tear off the can (previously smoked with a candle) and drill and tap for a set screw. Lead may be melted over a gas stove in a cast iron fry pan.

The cone counterweight arm *K* is a tinsmith's job and requires no great accuracy. This method of attaching the counterweight to the tube is due to Scanlon of Pittsburgh. Rod *G* may be tinned and cast into the small end of the cone with lead. Any misalinement will be taken care of by the eccentric weight.

The Pier: If heart-breaking effort has been expended in producing a good mirror and a sturdy and well made mounting, then it would be poor judgment indeed to erect it on a flimsy, spindly support. With concrete so cheap, it is no great labor to pour a substantial pier, in keeping with the rest of the instrument. There are a few general points to be borne in mind. See Figure 3.

For the standard 6″ mirror of 4′ focal length, the top of the pier will be about 10″ x 12″ in cross-section. Let this section increase until it is 12″ x 14″ at the bottom. This gives a 1″ batter at the bottom and clears the mirror cell when the tube is vertical. However, the weight of the instrument is not exactly centered over the pier, but lies a little to the north. Hence, flare out the base, as shown, to let the weight come at the center of the foundation slab.

The footing, as drawn, would go all right out here in southern California, but would not do at all for locations where frost goes deep into the ground. Anyway, see that your 'scope sets "four square" on, and into Mother Earth.

The drawing shows a bicycle seat, installed for those who want to take it easy. Its height above the ground and distance below the eyepiece are about as shown. In any case, the pier should have such a height that the telescope tube, when vertical, will clear the ground by a few inches.

One of the weak points of the Newtonian telescope, as applied to a fixed eyepiece mounting, is that the entire tube must be supported at one end instead of at the middle, as in the German offset type, and must therefore have more counterweighting. The Cassegrain is more adaptable, from this standpoint. The tube is shorter and can be balanced in Dec. without adding weight. The necessary weight needed in R. A. could probably be contrived as in Figure 4, without interfering with the observer's solar plexus. I have never seen one nor made one, except on paper, and I would like to see it tried out.

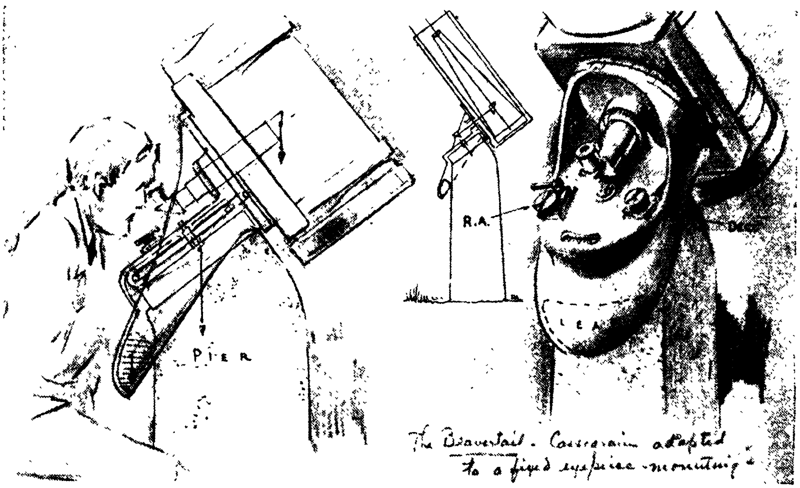


FIGURE 4

Well, there may be enough ideas and suggestions here to give the amateur a better understanding of how the shapes, sizes and relative proportions of a fixed eyepiece telescope are evolved. It may dispel certain misgivings entertained by those who wanted—but didn't dare—to make their own mountings out of metal. My own experience has been that the fun of watching the mounting grow fully equals the joys of making the mirror.—*Corona Del Mar, California, Sept. 1, 1935. Revised to Feb. 12, 1936, Pasadena, California, and to August 14, 1936, Cranford, N. J.*

The Building of a 19-Inch Reflecting Telescope *

By R. K. Young

The department of Astronomy in the University of Toronto, although it has existed as a separate department for over 20 years, has no observatory for research and instruction. Courses are offered to students in general astronomy, spherical astronomy, theoretical astronomy and astrophysics. The University has had the co-operation of the small observatory of the Metrological Service of Canada for the purpose of instruction in the use of the equatorial and transit instruments. It has always been the endeavour of Dr. Chant, the head of the department, to foster a wide interest in the subject, both within and outside the University, and to emphasize the need for an observatory. It is to be hoped that the project will not be delayed much longer.

I suggested to Dr. Chant in 1926, that it would be possible to construct a telescope privately, capable of doing useful research in many lines of astronomical work, and although rather diffident to using so much time for purely mechanical work, that I would be willing to undertake the task if we could find means to house the instrument. We decided to build as large a telescope as we felt we could complete in a reasonable time and we were confirmed in this decision because we had in mind the design and construction of a much larger instrument. The first-hand information obtained in building the smaller telescope would be extremely valuable in crystallizing our conceptions of what would be required in a bigger one.

The present article is a description of the design and construction of a 19″ telescope. It is published here because we think it should not be beyond the powers of the ambitious amateur to construct a similar or better one. It has been completed with the aid of a very modest workshop and occasional outside help for such work as could not be done on a lathe. It has taken about two years to construct, using only spare time in holidays and such time in the evenings and week-ends as available outside of university duties. The cost of the material and incidentals were roughly as follows:

1. Optical parts purchased, including plane mirror, finder lenses, eye pieces and disk for large mirror	$ 346.00
2. Outside work done, gear cutting, patterns, etc.	625.00
3. Castings, motors, bearings, incidentals	529.00
Total	$1,500.00

There are some very excellent works published on the grinding and polishing of mirrors, among which may be mentioned, "The Reflecting Telescope" by George W. Ritchey, in the Smithsonian Contributions to Knowledge, being

* Reprinted by permission, from the *Journal of the Royal Astronomical Society of Canada*, January 1930. [More and more amateurs are building or planning to build fairly large telescopes. The one described in the present chapter makes appeal because of its ruggedness and clean lines. The author is now Director of the David Dunlap Observatory of the University of Toronto, not built when the article was written.—*Ed.*]

part of Volume XXXIV; "The Amateur's Telescope," by the Rev. W. F. A. Ellison; "Amateur Telescope Making," by the Scientific American Publishing Co. We particularly recommend the last reference for the guidance of the beginner. The descriptions of the mounting in these books are not so satisfactory as for the mirror, and the ordinary amateur is inclined to mount his telescope in a very simple and inexpensive style. There is no doubt that a great deal of pleasure and profit may be obtained with even a crude mounting but labor spent on mounting will be amply repaid in the pleasure of using the telescope, more especially if the telescope is to be used for useful research work. As additional references, the beginner might read the very excellent description of the 72″ reflecting telescope of Victoria, B.C., published as the first number of the Publications of the Dominion Astrophysical Observatory, and a book entitled "The Telescope," by Louis Bell, published by the McGraw-Hill Book Company.

The Mirror

The main mirror consists of a piece of Pyrex glass 4″ thick and 19½″ in diameter, which we received from the Corning Glass Works in March, 1926. The simplest material for the amateur to select for small mirrors is ordinary plate glass, the thickness being from $\frac{1}{5}$ to $\frac{1}{10}$ the diameter. The beginner might try a plate of chromium steel to advantage if he is of an experimental turn. This material will take a high polish and retain it for many years and requires no silvering. It has not however been used and would be an experiment. For mirrors more than 12″ in diameter steel is rather heavy, and ordinary plate glass is not of good enough quality even if it could be obtained of the required thickness. What is desired is a substance with small expansion with heat and of great rigidity. Quartz disks possess these qualities to an admirable degree but at the time of beginning the 19″ they were in the experimental stage and could not be obtained more than 12″ in diameter. They are available in much larger sizes now. Pyrex glass, as is well known, was developed on account of its small coefficient of expansion with heat and it appeared to me to be the best material. It has the drawback, that it is very difficult to melt and consequently difficult to free from bubbles in the pouring. Large disks are usually much marred by these defects. The disk we obtained was rather bad but, as no bubbles of any size would come near the finished surface, I decided to use it.

The disk as it came to me from the makers was about half-an-inch thicker at one edge than at the other and the sides were much seamed. The first task was to shape the disk. I constructed a fairly large grinding table with a rotating turntable in the center. In order to true up the sides of the disk, I placed a brass band about 4″ wide and $\frac{1}{16}$″ thick around the glass and fed Carborundum and water to it as the disk rotated. It proved a very noisy affair but reasonably effective. The turntable is shown in Figure 1, where the disk is also shown after it had been trued and a hole drilled through the center. The turntable was operated by a system of belts and pulleys beneath

the table which are not shown in the photograph. The motive power was furnished from the workshop motor. An iron tool about 12" in diameter and ¾" thick was used to grind the top flat and parallel with the bottom. By bearing down when the tool was resting on the high side, the disk was gradually trued up. The whole process took quite a little muscular effort but not a great deal of skill or time. About two weeks after the reception

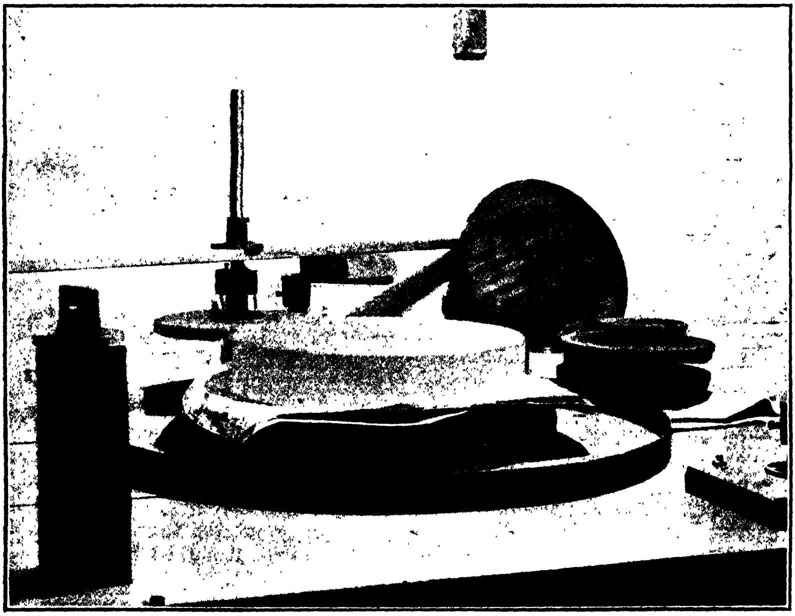


FIGURE 1

The glass disk after it had been ground to shape and a hole drilled through the center. The glass tool is shown to one side.

of the glass it was brought to shape, a comparatively short time compared to the tedious but interesting months of labor it took to figure the surface.

The final surface of a reflecting telescope mirror is in the form of a parabola, to which the equation in Cartesian geometry is, $y^2 = 2Rx$. The focal length of the mirror is $R/2$. In Figure 2, y is the distance of any point, such as P, from the axis AD; and x, the depth of the mirror below the chord joining two points on the surface, each at a distance y from the axis. In the present case, the focal length was to be 125" so that the equation to the final parabola would be $y^2 = 500x$. The depth of the curve at various distances from the center is readily computed to be that shown in Table I.

TABLE I

Distance from axis	Depth	Distance from axis	Depth
1″	.002″	6″	.072″
2″	.008″	7″	.098″
3″	.018″	8″	.128″
4″	.032″	9″	.162″
5″	.050″	9.5″	.180″

The beginner may not realize how nearly the surface approximates to a sphere or, what amounts to the same thing, how closely the curve *BPHA* in Figure 2, which is the parabola, can be made to fit a circular arc. In order

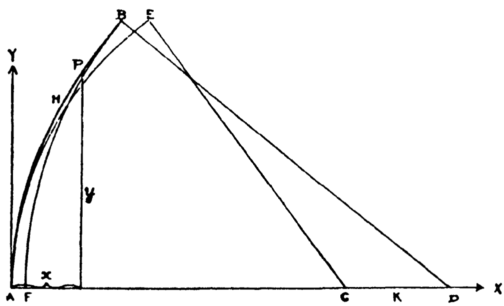


FIGURE 2

to show this, imagine a circle described with center at C and radius AC, equal to 250″. The equation to this circle is

$$(x-250)^2+y^2=250^2,$$

or

$$x=250-\sqrt{250^2-y^2};$$

and it may be readily shown that for any given y, the difference between the x for the sphere and the x for the parabola is, to a very close degree of approximation, $8\times 10^{-9}y^4$ inches. For the outside of the mirror, where $y=9\frac{1}{2}''$, the difference equals BE and can be computed to be 0.000,006,5″. The small difference between the sphere and parabola is quite below any ordinary method of measurement and the first step in grinding the mirror is to obtain the sphere. The small amount of glass which has to be removed afterwards is polished away by the so-called process of figuring.

The 12″ cast iron tool was used to hollow out the disk until micrometer measures indicated that the depths shown in Table I were obtained. All this work was done with coarse Carborundum, grade No. 40, and the grinding stopped a little short of the computed depths, leaving the last few thousandths of an inch to be removed by fine grinding. A glass tool was then substituted for the iron one. This tool is shown in Figure 1, which also shows the manner

of operating the tool on the glass. A long arm was pivoted at one edge of the grinding table and the glass tool fastened near its center. The exact position of the tool could be adjusted by means of various holes in this arm, and at the same time it was left free to rotate. The operator, holding the end of the lever arm, could move the tool latterly over the mirror with any desired stroke. The details of the process of fine grinding and obtaining a surface ready to polish are fully described in the references quoted, and I shall not describe them here, further than to say that this part of the work was very satisfactory and the desired result easily obtained and that in a comparatively short time the disk was ready for polishing.

I followed the procedure described by Ritchey in polishing, using resin and turpentine for forming the tool, and rouge as the polishing agent. At first I used a built up tool from pieces of wood reinforced on the back by strips of angle iron and had considerable difficulty with the tool warping.

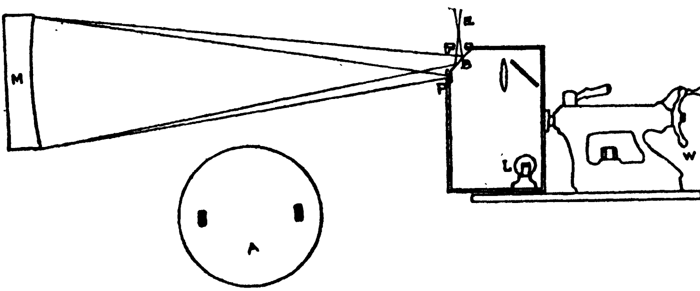


FIGURE 3

The apparatus for measuring the radius of curvature of the various zones. Light from L illuminates the pinhole P, and the image of P is formed at E. A knife-edge slides across the top of the box and determines the exact position of the focus.

Eventually I abandoned this tool and made an aluminum one, which was much more satisfactory and the surface brought to a satisfactory polish.

As soon as the mirror was polished I tested it to find out how nearly I had succeeded in obtaining a spherical surface.

Figure 3 shows the apparatus for measuring the radius of curvature of the various parts of the mirror. The method of grinding ensures the mirror being a true figure of revolution and so it is necessary to test zones at various distances from the center only. Light from the 24 c.p., 12 volt, light L is concentrated on a small piece of opal glass in front of a small pinhole at P. Light from this source, which is placed near the center of curvature of the mirror, is returned to the totally reflecting prism at B and bent upward so that the eye placed at E sees the whole mirror flooded with light. By moving the apparatus forward or backward by means of the screw on the tail stock of the lathe on which the light source was mounted, and sliding a safety razor blade back and forth over the top of the box, between the eye and

the beam, the position of the focus could be determined. One revolution of the wheel w moved the source of light $1/10''$ and the circumference being divided into ten equal parts, estimations could be made to the thousandth part of an inch. In practice the mirror was covered by means of masks such as that shown at A, and the radius of curvature of the various zones on the mirror determined.

As indicated before, the sphere is changed into a paraboloid of revolution by removing a very small amount of glass, an amount which could be polished away in a very short time, provided it could be done correctly. There are three ways to effect the figuring, viz, by removing glass from the outside, by removing glass from the center, or some from the outside and some from the center. To see this examine Figure 2. The parabola is the curve $BPHA$. Let the co-ordinates of the point B be x_0, y_0. The equation to the normal at the point B is

$$(y - y_0)R + (x - x_0)y_0 = 0,$$

and this cuts the axis Ax in the point $x = x_0 + R$, or D. With D as center and BD as radius, describe the arc of the circle BF, cutting the axis Ax in F. The distance AF is given by

$$AF = x_0 + R - (R^2 + y_0^2)^{1/2}.$$

The sphere may be changed into the parabola by removing the cap of glass BAF and the focal length obtained will be $R/2$. In order to obtain this we must start with a sphere of radius

$$x_0 + R \text{ or } R + y_0^2/2R.$$

The amount which must be removed is shown by the full curve in Figure 4. It may be shown that the total mass of glass which must be removed is given by

$$M = \frac{\pi y_0^6 \rho}{24R^3},$$

where ρ is the density. For a glass of specific gravity 2.5 this amounts to the surprisingly small quantity 0.25 grams or 3.9 grains. In this case the polishing is done at the center.

With C as center and CA as radius, describe the arc of the circle AE with a radius equal to R. We could change the sphere into the parabola by removing the cap of glass ABE, and in this case we would polish away the outer edge. The amount of glass which would have to be removed at various distances from the center is shown in curve II, Figure 4, and the total mass of glass which would have to be polished away is just the same as before.

Take a point P on the parabola and draw the normal. The normal will cut the axis in some point K lying between C and D. If we describe a circle with K as center and KP as radius, it will touch the parabola at P and lie between A and F and also between B and E. We could remove some glass from the outer edge and some from the center to change the sphere to a parabola. In this case the total amount to polish away is less than before.

If the point P is taken so that its x co-ordinate equals $x_0/2$, the amount of glass which must be removed is a minimum. The amounts at various distances from the center are shown in curve III, Figure 4. The total amount of glass to be removed in this case is less than one grain.

The usual method of procedure is to polish away the center. As the work

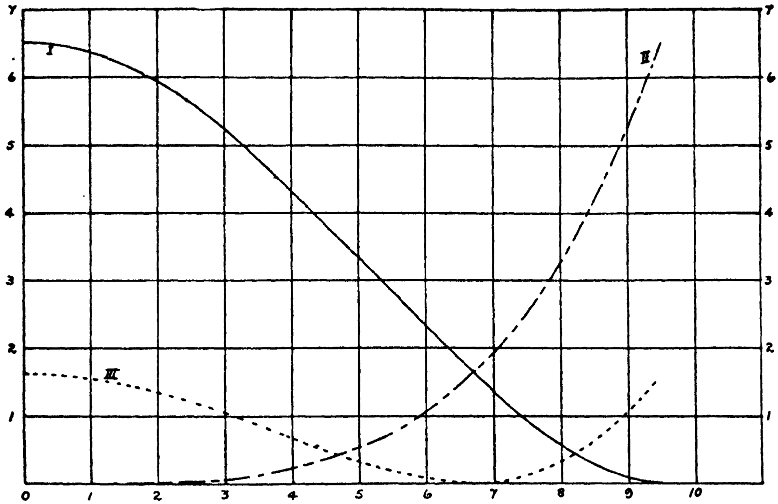


FIGURE 4

Curves showing the amount of glass which must be polished away to parabolize a sphere. Ordinates are expressed in hundred-thousandths of an inch. Abscissae are distances from the center of the disk. I, polishing from the center. II, polishing from the edge. III, polishing some from the center and some from the edge.

progresses we test the radius of curvature frequently for the various zones. It is necessary to be able to interpret these measures in terms of the shape of the mirror. One can readily show that if we test the mirror in zones of width Δs and that if ΔF is the error in radius of curvature of any zone whose center is at an ordinate y from the axis, the distance D by which the inner edge of this zone is high or low, beyond that of the contiguous zone farther out is given by

$$D = \frac{\Delta s \ \Delta F y}{R^2}.$$

From this formula we may construct the actual shape of the surface in relation to the paraboloid required.

In order to illustrate the use of this formula I give a set of readings made in the earlier experimental stages, together with the curve representing the shape of the mirror.

TABLE II

Zone	Measured Focus	Parabolic Focus	ΔF	$\Delta F \Delta_{8y}$ $R^2 10^{-7}$
9½–8½	.000	000	000	000
8½–7½	−.048	−034	−014	−17.9
7½–6½	−.048	−064	+016	+17.9
6½–5½	−.082	−090	+008	+ 7.8
5½–4½	−.090	−112	+022	+17.6
4½–3½	−.120	−130	+008	+ 5.0
3½–2½	−.128	−144	+016	+ 7.8
2½–1½	−.140	−154	+014	+ 4.4

The columns in Table II are consecutively, (1) the limits of the zone measured, each zone being 1″ wide. (2) The measured position of the focus in

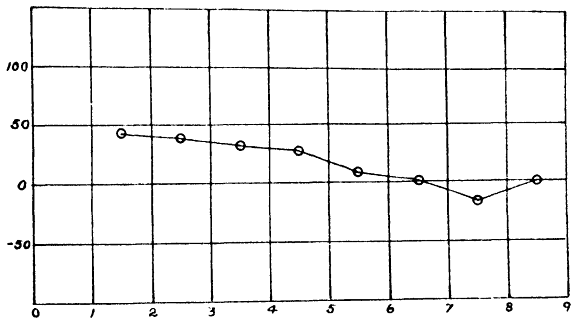


FIGURE 5

The condition of the surface shortly after starting parabolizing. The ordinates are expressed in ten millionths of an inch above or below the required surface, and abscissae are distances in inches from the center of the mirror.

inches, the outer zone being the starting point from which the others are measured. (3) The calculated foci for a parabolic mirror, the numbers in this column being obtained from Table I, because the aberration at the center of curvature for any zone equals the depth of the mirror below that point when tested by moving both the knife-edge and source of light. (4) The amount the measured aberration differs from the computed. (5) The error in the surface expressed in ten millionths of an inch. The first and last columns are plotted as a graph in Figure 5. At that time there was a low spot about 7½″ from the center.

I used local polishers almost entirely to produce the desired figure, smoothing up the surface from time to time with a full-size or two-thirds-size polisher. I shall not describe any of the methods used in making the polishing tools as these are treated very fully in the references given, but it may be of service to someone if I emphasize a few points. Before starting to polish be

sure that you know the shape of the mirror. This may involve repeated measures, with precautions being taken that the room is at a uniform temperature and the air steady. See that the tool fits the glass. This is especially necessary with the large polishers. I usually allowed the large polishers to *cold press* for several hours before using. Try to get a room for testing where the air is steady. I had some difficulty in this regard. The workshop was in a basement and during the summer months, when there was no furnace going, the conditions were quite good. As soon as the furnace was started in the fall there was too much difference between the temperature in the basement and outside and I found that air currents coming from the windows made it impossible to get satisfactory readings.

When the figure seemed to be right, as nearly as could be judged by the visual knife-edge tests, I made a photographic test by the method described in the Dominion Astrophysical Observatory Publications, Volume I.* The results are given in Table III, and express the final shape of the mirror.

TABLE III

Zone	Measured aberration	Computed aberration	O-C	Equivalent O-C at Focus
9	8.26	8.22	+.04	+.01
8½	7.50	7.34	+.26	+.06
7½	5.35	5.71	−.36	−.09
6½	4.05	4.29	−.24	−.06
5½	3.15	3.07	+.08	+.02
4½	1.59	2.05	−.48	−.12
3½	1.15	1.24	−.09	−.02
2½	1.26	0.63	+.63	+.16

The aberrations are expressed in mm. The center zone is covered up by the secondary mirror which is 5″ in diameter. Outside of this zone the greatest departure is in the 7½″ and 8½″ zones, but all are fairly small. One can compute from these numbers the angular diameter of the mean circle of confusion of the image of a star, and it comes out 0″.16. The theoretical diameter of the diffusion disk for a 19″ telescope due to diffraction is 0″.24 so that the telescope should theoretically give almost perfect definition.

Mounting

A general view of the mounting is shown in Figure 6. I have chosen the conventional form of equatorial mounting with the tube mounted on one end of the declination axis. The telescope is meant to rest on a cement pier rising two or three feet from the floor so as to give room to walk underneath the mirror.

The tube is of the open type. It consists of the central casting which supports the open tubular construction, and on one side of the central casting

* These publications are now difficult to obtain, but may be consulted in some astronomical libraries. However, the test referred to above is the Hartmann test, and is described in another chapter of the present volume.—*Ed.*

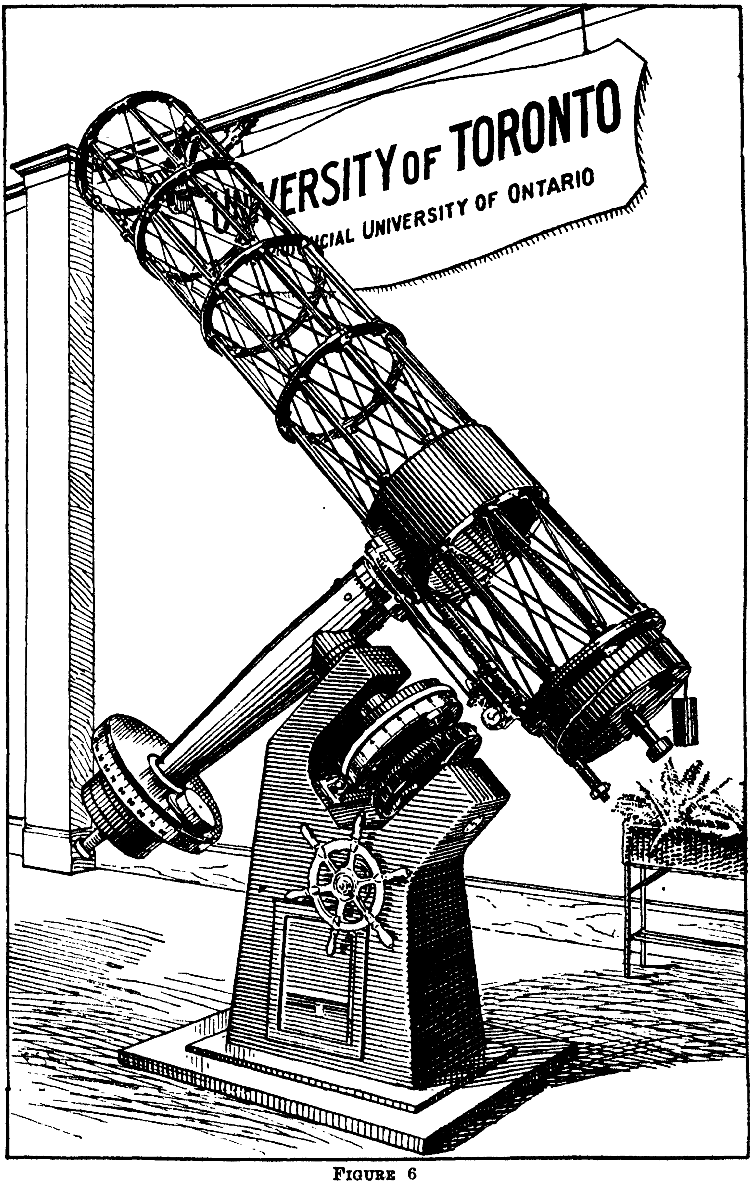


FIGURE 6

is a boss which holds it to the declination axis. The framework of the tube is built up from light steel tubing in sections which are fastened together by steel rings. The advantages of this construction are that the tubes may be made progressively lighter toward the upper end of the tube, and the lower end, when made heavy enough to carry the mirror, naturally balances the longer end. Also the system of braces, which consist of steel rods threaded right and left hand, can be adjusted to bring the geometrical axis of the tube exactly at right angles to the declination axis. The short tubes which connect the various sections are also threaded right and left hand and by adjusting these in connection with the brace rods the tube may be made to

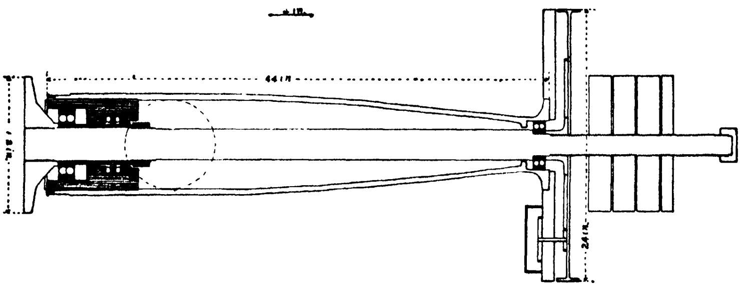


FIGURE 7

A longitudinal section through the declination axis and housing. Note scale.

bend in any direction or to rotate screw fashion, either right or left hand. If I were making the tube again, I would substitute aluminum tubing for the steel.

The mirror cell at the bottom of the tube consists of a single casting with a flange to bolt it to the bottom ring of the tube. The mirror rests on three disks supported from the bottom of the casting on ball-and-socket joints which can be raised or lowered to effect collimation. There is about ¼″ clearance around the edge of the mirror for packing. Although very simple, this method of mounting seems to me to be sufficient. The complicated system of levers and counterweights is quite unnecessary unless the mirror is very thin. The mirror is ground, polished, and figured on a simple turntable, placed on its edge for testing, without any special support. Its position and use in the telescope tube makes no greater demand on its rigidity than the conditions of testing, and if the mirror shows a good figure in the laboratory tests it should not be necessary to introduce elaborate methods of support in the telescope.

The secondary mirror at the top of the tube is a 5″ flat made by J. W. Fecker of Pittsburgh. It is supported in a light aluminum casting carried by four strips of saw-steel about 3″ wide which reach to the sides of the tube. The supports for these strips on the tube can be adjusted for focus and the mirror cell can be rotated to bring the image out to the edge of the

tube in any position. The plate carrying the eyepieces can be fastened at either side of the tube, toward the pier or away from it as most convenient. A second mirror cell can replace the Newtonian mirror when the telescope is to be used in the Cassegrain form.

The declination axis and housing is shown in Figure 7. The axis proper consists of a cold rolled shafting 3″ in diameter and the housing is a molded

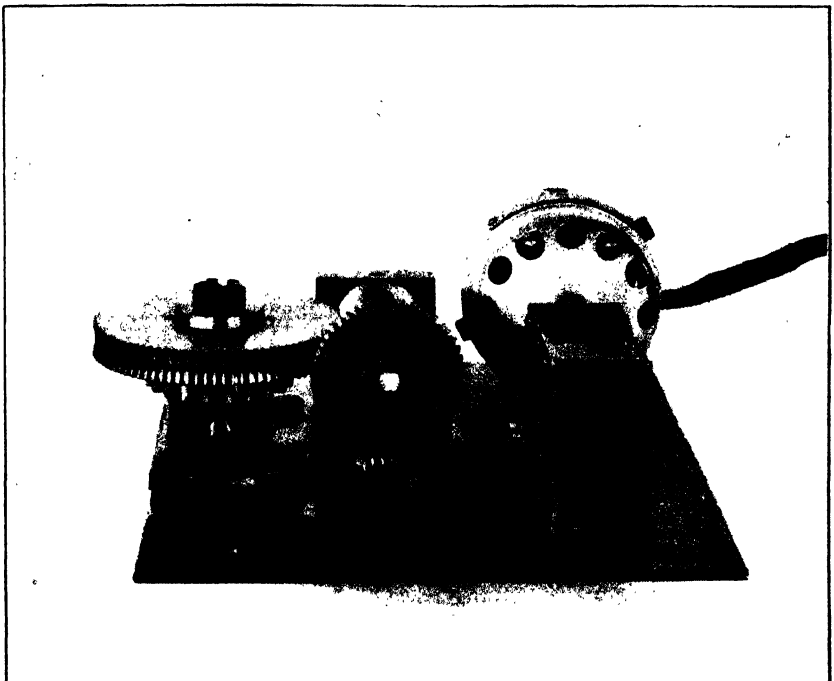


FIGURE 8

The motor and gear train for slow motion in declination.

casting carrying at its inner end the alining and double-thrust bearings shown in the figure, and at its outer end a simple alining bearing. These bearings are SKF and the tube moves very freely but without perceptible play. When the tube is balanced, about two ounces applied to the upper end of the tube will start it moving. The main part of the counterweight for the tube, consisting of a large cast iron flange, is fastened to the declination housing, and four cast iron weights threaded on the end of the declination axis proper serve

for adjustment. The declination circle consists of a bronze wheel, 2′ in diameter and 2½″ face, rigidly fastened to the declination axis. It is divided into single degrees. In order to be able to read the declination more accurately than this when setting on a star, I introduced the same kind of gear system as used in the 72″ telescope at Victoria, B.C. The declination circle carries a gear wheel of 270 teeth 18 D.P. and this engages by a train of gears to a small drum carried by the counterweight flange. This small

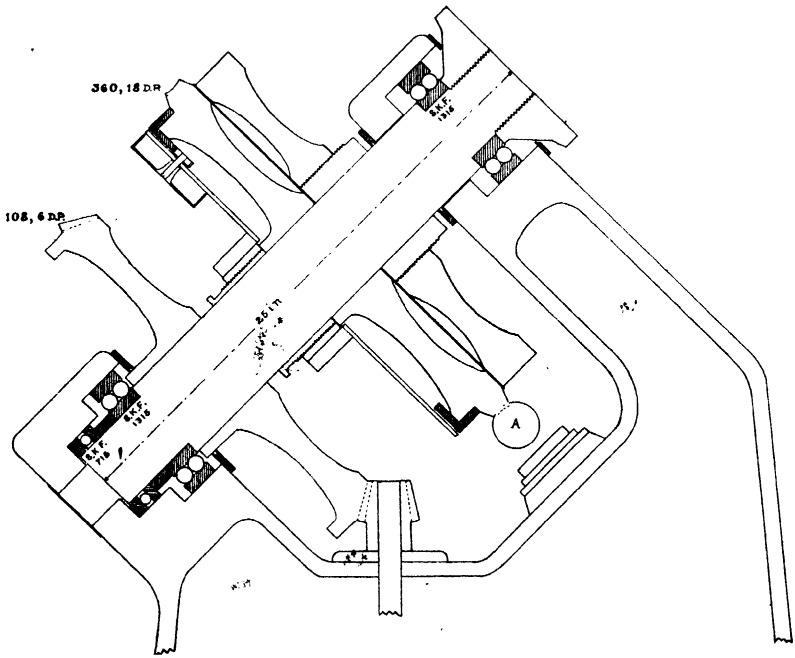


FIGURE 9
A section through the polar axis and the top part of the pier, showing the gearing and the various driving wheels and clamp in right ascension.

drum is a very light aluminum wheel about 7″ in diameter and makes one revolution for a motion of the telescope in declination of ten degrees. Estimation of declination can be made to single minutes of arc when viewing the drum from the position the observer occupies when moving the telescope. The clamp in declination consists of a band of iron on the declination housing which can be clamped or freed from the housing by a hand wheel near the eye end of the finder on the tube. Fastened to this band is an arm about 18″ long which has a small arc of a gear wheel cut in its outer end. This engages with the slow motion gear in declination shown in Figure 8. A hand

switch carried by the observer can be made to operate the declination motor in either direction for the purpose of fine adjustment. When running at full speed this motor will move the telescope about one degree in four minutes of time. By giving the switch a quick tap the tube can be moved as small an amount as one-tenth of a second of arc.

The polar axis is made from a piece of 4″ cold rolled shaft and carries at its upper end a flange which bolts it to the declination housing. A cross

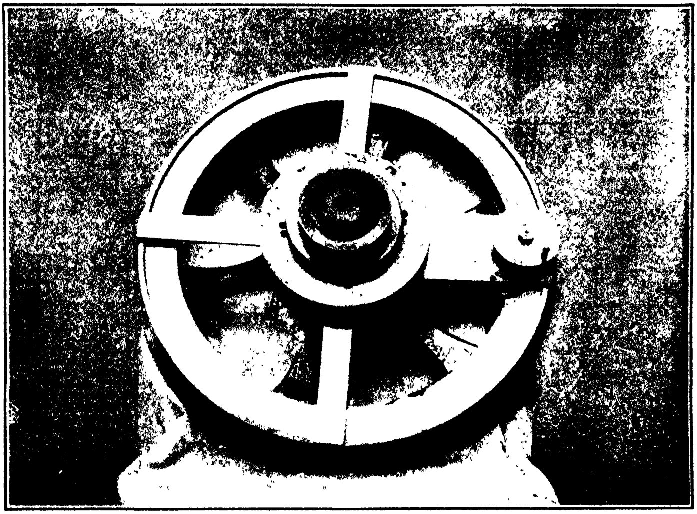


FIGURE 10

The right ascension worm gear and the index arms with the drum for accurate readings.

section through the polar axis is shown in Figure 9. This section shows in order the various wheels carried on the polar axis. Starting from the bottom there is first the fast-motion hour circle wheel, 108 teeth, 6 D.P., which engages a pinion and communicates with the hand wheel shown on the side of the pier in Figure 6. This wheel is rigidly fastened to the axis and a flange on its edge is graduated to indicate the hour angle of the telescope at any time. Above the hour circle wheel is the wheel for the clock drive. This wheel consists of a cast iron center with a bronze ring shrunk on its outer edge, the bronze ring forming the worm gear of the drive, 360 teeth, 18 D.P. It turns freely on the axis but can be clamped to the axis by the single-disk clutch which is shown immediately above it. On its lower edge it carries a sidereal circle which can be adjusted at the beginning of the night to read right ascensions directly. The sidereal circle is graduated to four minutes and in order to set more accurately there is a set of gears which engage

with the small drum shown on the index arm in Figure 10. The small drum makes one revolution in ten minutes. The operator standing beside the pier turns the hand wheel until the R.A. reading is correct to the nearest 5 seconds and then clamps in the clock drive by the single-disk clutch. The worm screw is indicated at *A* in Figure 9. It has three degrees of freedom, not

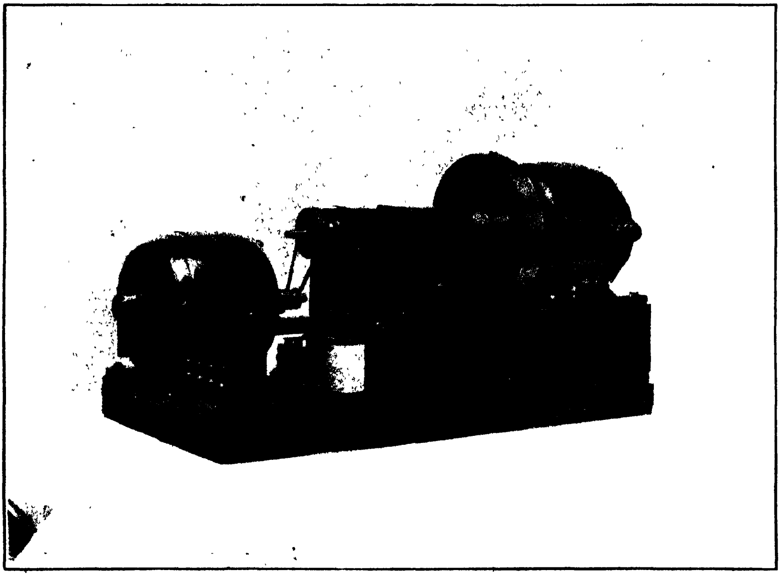


FIGURE 11

The electric drive.

shown on the cut, which make it possible to obtain the proper mesh with the worm gear. The worm gear and sidereal circle are also shown in Figure 10. In this plate a temporary axis has been inserted in order to carry the index arms and the small drum for fine reading in right ascension.

THE CLOCK

The astronomical department possessed a gravity driven clock made by Cooke but I was doubtful whether it was large enough to serve. Moreover there is always more or less trouble with a gravity drive in this climate, due to thickening of the oil in cold weather. I decided to build an electrical drive. I wanted to do this as an experiment and the results have been very successful. I chose the system invented by Mr. Gerrish, of the Harvard College Observatory, and described in Bell's book, "The Telescope." A small

motor furnishes the power and the speed of the motor is controlled from a sidereal clock which allows power to be fed to the motor intermittently to keep it running in unison with the clock. Figure 11 gives a general view of the clock and a section through the gearing is shown in Figure 12. The entire cost of the parts was less than \$75, the main item being the motors.

The driving motor turns the worm gear *A* (Figure 12) at 1725 revolutions per minute when running at its normal rate. This gear engages with the

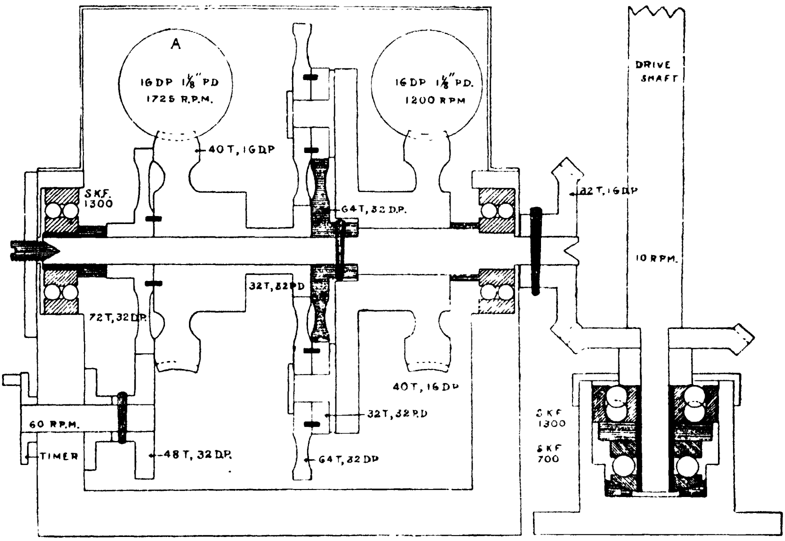


FIGURE 12

A section through the electrical clock gearing.

timer wheel, as shown in the diagram, which interrupts the current fed to the motor and keeps the timer wheel running 60 revolutions per minute, thus reducing the motor speed to 1600. The current is flowing for about 0.60 to 0.75 of a second and the balance wheel carries on for the rest of the second. A little difficulty was experienced in getting the balance wheel to run smoothly, but by inserting small weights around its edge, as in the balance wheel of a watch, it was finally adjusted so that no vibration could be felt. The electrical circuit and the manner in which it operates are fully described in Dr. Bell's book.

The driving motor communicates through a differential train of gears to the driving shaft. The normal rate of rotation of the driving shaft is ten revolutions per minute when the differential gear is held; and in order to provide slow motion and guiding motion in right ascension I introduced a second motor to operate the differential gear. The second motor makes 1200

revolutions per minute and when running it adds or subtracts from the rate of rotation of the driving shaft according to the direction of its rotation. When running at full speed and subtracting its rate from the clock drive, the driving shaft has a slow rotation forward and when running at full speed in the opposite direction, the driving shaft turns at nearly double its normal rate. The same hand switch which operates the declination slow motion operates this motor also, so that the observer by pressing the suitable button controls the telescope in right ascension and in declination. A sharp tap on the right ascension button can make the telescope move as small an amount as one one-hundredth of a second of time. I have not had the opportunity of testing the following of the clock on the stars but have had it running in unison with the sidereal clock which it follows perfectly. We hope soon to find a suitable place to house the telescope so that it may be used for instruction in the university and for research work.

The Schmidt Camera—Introductory *

By PROF. HENRY NORRIS RUSSELL, PH.D.

Chairman of the Department of Astronomy and Director of the Observatory at Princeton University; Research Associate of the Mount Wilson Observatory of the Carnegie Institution of Washington

Everyone who has used a camera knows that a good lens should meet severe conditions. It must bring the rays to a *sharp focus*, not only at the center of the image but over a *wide field* of view. It must bring light of all colors to the same focus—that is, it must be *achromatic;* and it is very desirable, though not necessary for all purposes, that it should give a bright image, permitting short exposure—it must be *fast.*

We all know, too, that to get an achromatic image even approximately, our objective must be made of two component lenses of different kinds of glass. To get a sharp focus over a wide field there must be three or four components in the objective, instead of two. Finally, a fast lens must be of large diameter compared with its focal length.

To meet all the conditions, which have here been merely outlined, demands the highest skill of the designer and the optician, so that good lenses are necessarily costly, even in the small sizes used in ordinary cameras. For the larger apertures used in astronomical work there is added the great difficulty of casting perfectly flawless disks of glass.

Some of these difficulties may be altogether removed and others greatly diminished by using mirrors instead of lenses. A reflecting telescope is perfectly achromatic, and the ratio of its aperture to its focal length can be made much larger than is practicable for a two-component lens. Moreover, by figuring the surface to an exact paraboloid of revolution, all the light of a star may be brought to a geometrically exact focus—barring the inevitable effects of the diffraction of light waves, which are alike in all instruments of a given aperture.

Despite these important advantages, the reflector has one very grave disadvantage. Its field of good definition is severely limited. The condition that all the parallel rays of a beam of starlight shall be brought by reflection to a sharp focus fixes the *form* of the mirror surface completely. It may be obtained by rotating a parabola about its axis. The only freedom left the designer is to determine the size of this parabola—that is, the focal length of his mirror—and of course to decide how large a portion of the infinite geometrical surface shall be arbitrarily brought into being upon his glass disk. But this paraboloidal surface will perform ideally well only when the stars' rays come to it along the direction of its own axis. If they are inclined to this at even a small angle, the rays reflected from different portions of the mirror will not converge to the same point. Those from the outer zone do not come to a focus at the same distance from the mirror as those from a zone near the middle of the mirror and their best approximation to a focus

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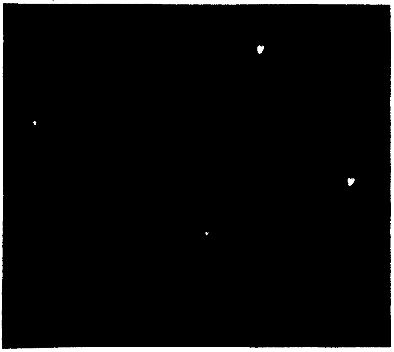
* Reprinted from the *Scientific American.*

is displaced laterally away from the center of the field, so that the image becomes a roughly triangular mass like a half-opened umbrella or a tiny comet with a wide, bright tail (Figure 1).

This "aberration" of the image is called coma. It is always present, theoretically, except at the very center of the field. Its amount increases proportionally to the distance of the star from the center, and also to the square of the ratio of the diameter of the mirror to its focal length. The



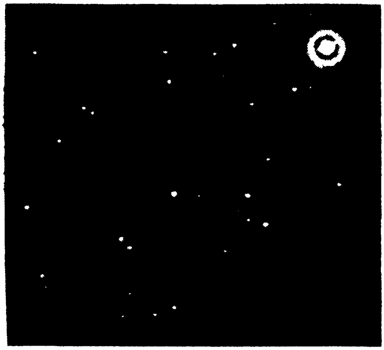


FIGURE 1

Left: A highly magnified section of a photograph made with a 12", f/4.5 Newtonian, showing comatic images (half opened umbrellas, pointing downward) at the edge of a 1½° field. Right: By contrast, a highly enlarged section of a photograph made with an 8", f/1 Schmidt camera made by O. A. and H. A. Lower and described two chapters farther on, showing the images at the edge of a 20° field. The Schmidt images show no coma, but there is a trace of astigmatism. This is unavoidable, and all Schmidt cameras of very short focal ratio will show a little astigmatism. The ring was caused by reflection from the back of the film.

brightness of the image of any extended object, such as a nebula, is proportional to this last quantity. It is therefore impossible, with a single reflecting surface, to secure a bright image and a wide field at the same time. The star images go bad not far from the center.

With an aperture one-fifth of the focal length, as in the 100" telescope at Mount Wilson, the deterioration of the images becomes perceptible to a trained observer at 3'.6 from the center, so that the field of really satisfactory definition is only one eighth of a degree in diameter. The 200" telescope will have to be made shorter in proportion to its diameter, to avoid enormously increased cost, and Dr. Ross calculates that the images will be really sharp in a portion of the plate less than one inch in diameter. It may be repeated that this property of the simple reflecting telescope arises from simple, though not quite elementary, considerations of geometry. It is incurable—unless we decide to make our telescopes more complicated in design. Then there are many ways of escape. By using two mirrors which divide the image-forming

work between them, additional degrees of freedom become available and coma may be eliminated over a wide field.

The first such scheme worked out in detail was by Schwarzschild, the most distinguished German astronomer of our times, in 1905. It employs a main mirror of small concavity, with a second more concave and of half the diameter placed in front of it (Figure 2). This gives a flat field, with good images over a region 2° or more in diameter, and has great light-power, since the effective focal length, as determined by the scale of the image, is three times the diameter of the large mirror. But the tube from one mirror to the other is 25 percent longer than for an ordinary reflector. The loss of one quarter of the light by interposition of the second mirror is not very serious.

A reflector of this type is under construction for the University of Indiana. A second type, in which the small mirror is convex, 30 percent the size of the big one, and much nearer to it, was designed by the French astronomer Chrétien. A 40″ telescope of this design has been constructed for the United States Naval Observatory by Mr. G. W. Ritchey.

It is also possible greatly to increase the available field of a parabôlic mirror by interposing a specially constructed lens not far in front of the focal plane. The very complicated theory necessary for the design of such "correctors" has been developed by Dr. F. E. Ross, and lenses of this sort

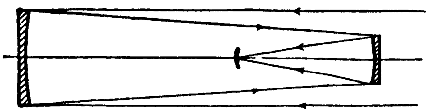


FIGURE 2

have been adapted to the 60″ and 100″ reflectors at Mount Wilson with great success, and will be provided for the 80″ in Texas and for the 200″ in California.

These devices, while of high value for use with large telescopes, do not permit the construction of mirrors with as favorable a speed-ratio as can be attained by the best lenses. A ratio of $f/3.3$ is about the best that has been attained, while specially designed lenses have gone almost to $f/1.0$. Such image-forming systems of short focus and great speed are especially important for astronomical spectographs. The collimation of such an instrument—a small reversed telescope which receives the diverging beam of light after its passage through the slit and turns it into a parallel beam so that it may pass through the prisms without distortion—has perforce to be designed with the same ratio of aperture to focal length as the telescope which feeds it. (Even with the reflectors this is small, for the spectographs are used with a secondary concave mirror which lengthens the focus.) When there is plenty of light a long camera behind the prisms gives a large image full of rich detail. But, for faint objects and especially for extended surfaces such as nebulae, a short camera is necessary. This increases the intensity of the image by diminishing both its length and its breadth. Moreover, the

spectral lines of the plate, being reduced images of the slit, are very narrow, and the slit may be widened, admitting more light without fuzzing up the negative perceptibly.

It was by inventing this short camera that V. M. Slipher at the Lowell Observatory succeeded, with a telescope of moderate size, in obtaining the first good, detailed spectrograms of the spiral nebulae, and so began one of the most striking advances of modern astronomy.

Now short focus lenses up to an inch or so in aperture can be perfectly well made, though it is skilled work. But a lens 6″ in aperture and of similar shape would be so thick that much light would be lost in passing through the glass, and would be extremely costly to make.

A most ingenious solution of the problem has been made by Dr. B. Schmidt of Bergedorf, in Germany. The "Schmidt camera" uses a mirror instead of a lens, and returns to a very old practice by making its mirror spherical. Now every telescope maker—amateur or professional—knows that

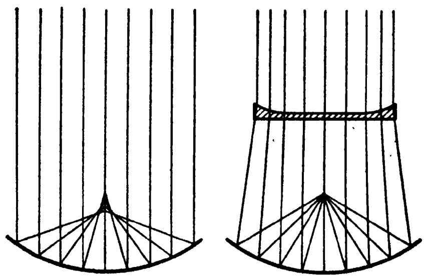


FIGURE 3

a spherical mirror is easier to make than a paraboloid—indeed most mirrors are originally made spherical and then parabolized by gradually polishing away the excess material. But a spherical mirror, as all workers know, gives a most unsatisfactory image. The rays reflected near the edge cross nearer to the mirror than those which come nearer the center, and no sharp image can be secured, as is shown in Figure 3, left (where the effect has purposely been exaggerated by taking the diameter more than twice the focal length).

This effect may be eliminated by changing the mirror to a paraboloid, but only at the price of introducing coma and narrowing the field of good definition. In place of this, Schmidt introduces a "correcting plate"—really a very thin, concave lens in front of the mirror. Its action is obvious from Figure 3, right. The rays near the center are very little deviated, while those passing near the edge are bent outward, and these strike the mirror at such angles that all are reflected exactly toward the same focus.

Even for the enormously exaggerated case shown in the picture, the plate is thin in comparison with its diameter, and its surface is considerably curved only near the edges. In practical application the curvature of the surface

is so small that it is only perceptible by optical testing. A plate 12″ in diameter, for example, will have surfaces which are never more than a few thousandths of an inch removed from planes. After it has been carefully figured to its proper shape one would take it for an ordinary piece of parallel-faced glass—unless, indeed, one applied the severe test of looking through it at a very oblique angle.

With such a correcting plate the central image of a star becomes sub-

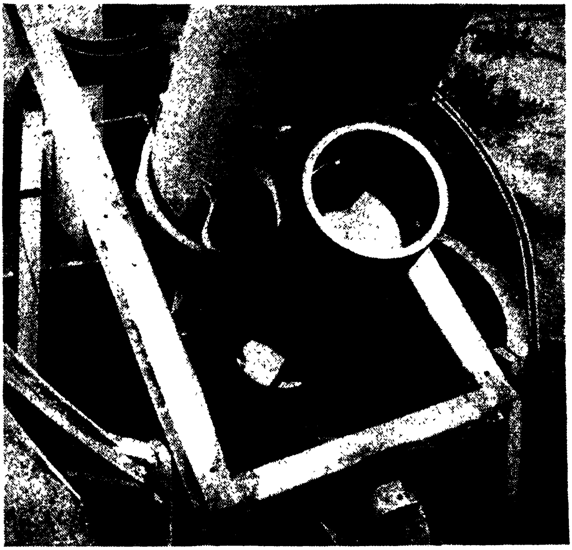


FIGURE 4

A Schmidt camera—the first of short focal ratio built in the U.S.A.—made by Dr. H. Page Bailey of Riverside, California, and attached to the tube of his 15″ Cassegrainian. It has a 9″ mirror of 19″ focal length, and a 9″ correcting plate stopped down to 8″. It was built in 1932 and gives fine performance.

stantially as good as with a parabolic mirror. (Theoretically there is a slight departure from achromatism, due to the dispersion of the glass, but this is usually negligible in practice.) But the great advantage of this device is that the images of objects several degrees from the axis are almost as good as those at the center of the field. The spherical mirror itself produces no coma—only spherical aberration, and this to exactly the same amount no matter whether the rays fall on it from one direction or from another, for all parts of a sphere are alike. Inclined rays differ from axial rays only in passing through the plate at an angle. Now the whole effect of the plate is to introduce a distortion into the beam of rays, just sufficient, when they traverse it squarely, to undo the spherical aberration of the mirror. Rays tra-

versing the plate at a moderately oblique angle will suffer very slightly greater deviations, the effect being a minimum for perpendicular incidence. As the deviations are small anyway, this change will be almost imperceptible, and the effect will be almost perfectly adapted to neutralize the aberrations of the mirror. In consequence, the images are good over a remarkably wide

FIGURE 5

The completed mounting of the 18" Schmidt telescope installed on Mt. Palomar. It was designed by Russell W. Porter. The primary has a diameter of 26", the correcting plate 18" and the plate holder 6". Focal length, 36" (f/2). The projection on the front is for supporting the 10° objective prism for producing star spectra. Synchronous motor drive. This telescope will be used in the search for super-novae. Mr. Porter with pipe at right. Note proportions of axis, etc.

area. Mr. Schmidt has obtained photographs having a workable field 12° in diameter.

A series of Schmidt cameras is under construction for the large spectograph at Mount Wilson. By careful calculation of the curve of the correcting plate, an extraordinarily high speed-ratio can be secured. A camera with ratio $f/1$ is in successful use, and one of $f/0.57$ is under construction, with an aperture 1¾ times the focal length! This should be of extreme value in observing faint stars.

At present this new device is likely to be of more service to the professional than to the amateur. The cross-section of the correcting plate is a curve of the fourth order, which must be calculated by the maker, and the figuring of the surface demands a rather unusual type of work. Moreover, the final focal image is not flat, but upon a spherical surface of radius equal to the focal length, so that special curved films would be required to cover a wide field. The very novelty of these problems, however, may be a challenge to the student who has already mastered the simpler technique of the ordinary mirror.—*Princeton University Observatory.*

[EDITOR'S NOTE: Professor Russell's later "hunch" was correct—the amateur did not stick at the "curve of the fourth order," and several Schmidt cameras made wholly or in part by amateurs are shown in the present chapter and in the next but one. Bailey's (Figure 4) was the first short-focus

Photo by E. L. McCarthy

FIGURE 6

Made in Chicago—see comment below.

Schmidt made in the U.S.A. by an amateur. The Lower Schmidt came next, followed by the large Schmidt at Mt. Palomar (Figure 5) and the one shown in Figure 6, though these jobs partly overlapped in time. In nearly all of these pieces of work, amateurs and professionals were working in cooperation. For example, in the case of Figure 6, the Chicago-Yerkes-Texas camera, C. H. Nicholson of Chicago, who made the optical elements, states: "Dr. Otto Struve, Director of the Yerkes Observatory, who is also in charge of the construction and operation of the new McDonald Observatory in Texas, indicated to the Chicago amateurs his inability to procure from professional makers two Schmidt cameras to be used in connection with the quartz spectrograph and the 82″ telescope of the Texas observatory. As a good deal of

original research hinged upon the procuring of these instruments, Dr. Struve suggested that the Chicago Amateur Astronomical Association attempt the task as one means of aiding in the advance of astronomical knowledge. Mr. William Callum and Dr. A. H. Carpenter, the guiding spirits of the Club, requested me to build the first camera.

"The specifications for this camera were that the mirror was to be of Pyrex, 122 mm clear aperture and 180 mm focal length, with a correcting place of UV glass at center of curvature and of 92 mm clear aperture.

"Although the mirror gave me no real trouble, I found the correcting plate very difficult to figure, for the reason that it was necessary to do all the correcting by fine grinding with small tools and then repolishing to examine the figure. This involved a great deal of time, as it is very easy to make large errors when figuring by grinding in this manner. Testing was done by pinhole at focus of the Schmidt camera and the knife-edge at focus of a 6″ telescope. All curvature was placed on the front surface, necessitating a convex curve at the center, changing to an equal concave curve at the edge of the plate.

"Upon completion it was tested by Dr. Morgan of the Yerkes Observatory Staff and found to yield star images as small as he had ever seen; their size being limited by the grain structure of the photographic plate.

"The mounting was designed by Dr. G. W. Moffitt of Yerkes and made by Gaertner."

Mention of the inability to procure a Schmidt camera from the professional optician is not included in order to reflect in any way on the professional. It seems likely that the professional saw in the production of the unfamiliar correcting plate a job which might turn out to be relatively simple or, on the other hand, might require a long time for the development of special technic. It would be difficult for him, therefore, to make an estimate on such a piece of work. The amateur, on the other hand, not having to make his living from optical work, can afford to spend an indefinite number of hours fussing and pottering with a given job until it just suits him. This also provides a possible reason for the fact that in other respects the amateur often can equal or even excel the professional—he can afford to take the necessary time to make this possible. In a few instances, however, amateurs have undertaken optical work as a vocation and then have soon found they had to make new arrangements with regard to time in order to make a living.

Schmidt enthusiasts will find an excellent article on the Schmidt, by Prof. C. H. Smiley of Brown, in the October 1936 number of *Popular Astronomy*.]

Theory and Design of Aplanatic Reflectors Employing a Correcting Lens

By Franklin B. Wright
Berkeley, California

Several attempts have been made to devise practical aplanatic systems (that is, systems free from both spherical aberration and coma) by utilizing two mirrors, or one mirror and one or two lenses. These include the Schwarzschild and Ritchey-Chrétien telescopes, the two-lens Ross corrector used in conjunction with an ordinary Newtonian telescope near its focus, and finally the Schmidt telescope. The first two of these are two mirror systems built like Cassegrains but with special curves, the Schwarzschild having a concave secondary mirror inside of the primary focus, which reduces the total equivalent focal length and brings the final image between the two mirrors, and the Ritchey-Chrétien having a convex secondary mirror closely resembling the conventional Cassegrain. The two-mirror types are described in considerable detail by Ingalls, and by Carpenter and Kirkham, in the *Scientific*

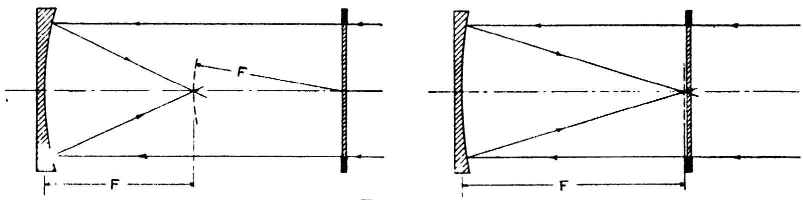


FIGURE 1

American, respectively for July 1932, and for June, July and August, 1933.

The present chapter deals with systems utilizing one mirror and a correcting lens, with the parallel rays from a distant object passing through the lens before striking the mirror. In the telescopes or cameras to be described the correcting lens has nearly plane surfaces, so that it has little effect on the overall focal length. The cell for mounting the lens acts as a stop which limits the aperture, the mirror being made larger than the lens, in order to catch the off-axis rays passing through the lens. The distance between mirror and correcting lens is a matter of choice, provided both members are figured with curves appropriate for the distance chosen. But there are two distances of special importance for general use, since each eliminates another form of aberration besides coma and spherical aberration. One of these distances produces the Schmidt telescope, and, for want of a better name, the other will be called the "short" telescope, referring to the shortness of its tube length compared with the focal length.

In the Schmidt telescope the distance between mirror and correcting lens equals approximately twice the focal length, the mirror being figured spherical. This combination is free from astigmatism, and, incidentally, from distortion of field also. The focal surface of best definition is spherical,

convex toward the mirror, with a radius of curvature approximately equal to the focal length (see Figure 1, at the left). Photographic films must be sprung to conform to this surface, in order to realize the remarkable perfection of this instrument. It can be constructed in extremely short focal lengths with good definition over a field at least 12° in diameter. There is a certain amount of chromatic aberration, due to the correcting lens, which varies with the cube of the f ratio. Ordinarily this is negligible, but it does establish a rather sharply defined limit below which star images deteriorate rapidly. A conservative limit for general photography is probably around $f/1.5$ for a Schmidt of about 8″ aperture.

The Schmidt camera principle has been applied with great success to

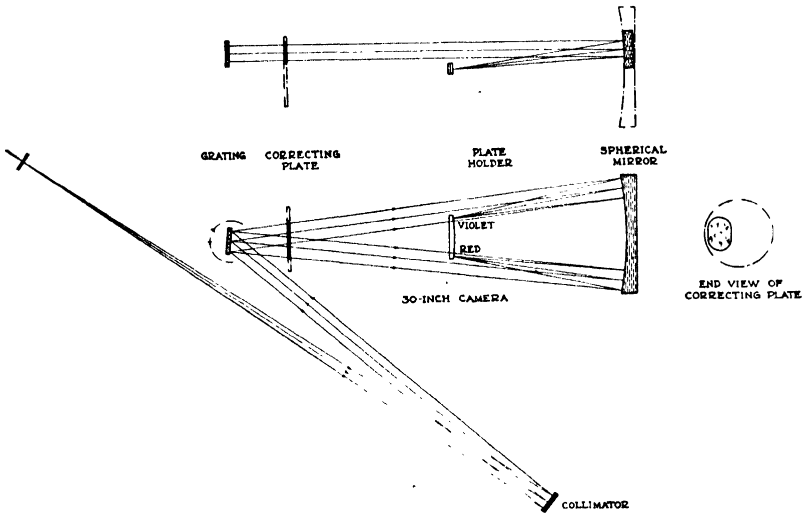


FIGURE 2

the photography of spectra, in conjunction with the 100″ telescope at Mt. Wilson, by Theodore Dunham. Through his courtesy a diagram of this arrangement is reproduced here (Figure 2). It is to be noted that only a portion of one side of the correcting lens is used, the remainder being cut off and discarded. For spectrograph camera work the f ratio may be shortened almost without limit, but the region of the spectrum in good definition will shorten as the f ratio is made smaller.

In the "short" telescope the distance between mirror and correcting lens approximately equals the focal length (see Figure 1, right). The mirror is figured to a curve which is nearly an oblate spheroid whose outer zones have their centers of curvature closer to the mirror than the central zone by approximately the amount $y^2/2R_0$, about the same variation numerically

as in the case of a paraboloid but in the opposite direction. This system is free from curvature of field; that is, the focal surface of best definition is a plane, which permits the use of ordinary flat photographic plates and plate holders. These could also be used with a Schmidt telescope, but the star images away from the center of field would be twice as large as in the case of a "short" telescope with the same optical dimensions.

Astigmatism rather than chromatic aberration limits the desirable f ratio of the "short" telescope. Chromatic aberration is a phenomenon affecting all parts of the field, but astigmatism appears only toward the edges and causes star images to be enlarged without destroying their symmetry, as would be the case with coma. The "short" telescope has less astigmatism in a flat field than any other aplanat having but two optical components. At an aperture ratio of $f/4$ the diameter of a star image due to astigmatism is about 1″ of arc ½° from center of field. It varies inversely with the f number and directly with the square of the angle from the center of field. With these facts in mind, and considering space requirements for the plate holder, it appears that about $f/3$, with a photographic plate holder of the right size to cover a 5° field, would be a reasonable limit for good practice in the design of "short" telescopes of around 8″ aperture, intended for general photography. However, a 4° field at $f/4$ should be noticeably better. One of the latter proportions could also be equipped with a diagonal and suitable eyepieces for visual observation.

Probably photography would be better done without a diagonal, with the plate holder supported by ribs directly at the focus. The 36″ Crossley reflector (Newtonian) at the Lick Observatory, a pioneer instrument in celestial photography, has for years been successfully used in this manner. If photography is to be done directly at focus, the correcting lens and mirror should preferably be figured for a separation a little greater than the focal length, to make room for the plate holder. An example of such a design will be given. The slight curvature of field introduced by this modification is negligible at $f/3$ or longer.

At the time of this writing no telescope of the "short" type has been made. However, there is a possibility that a spectograph camera will shortly be made on this principle at one of the leading observatories. For this kind of work it is advantageous to bend the photographic plate so that it is concave toward the mirror, with a radius of curvature approximately equal to twice the focal length. This would give excellent definition in a direction lengthwise of the spectrum for a large angle off-axis. Incidentally, there is an intermediate type, suitable for a flat field spectrograph, with the correcting lens separated from the mirror by 1⅓ times the focal length. This would give good definition, comparable with the above, without bending the plate. These types were noted as promising possibilities by the writer while examining the general theory of the already well-known Schmidt telescope.

In all of these telescopes the correcting lens neutralizes the spherical aberration which would otherwise be introduced by using a shape for the mirror which is not parabolic. Its figure is illustrated in exaggerated form by

curves A and B, Figure 3. The figures for the various possible types are practically alike, except that the "short" ones have greater variation than the Schmidt for a given f ratio. In fact, the correcting lens for a "short" telescope of $f/4$ would be interchangeable with the lens for a Schmidt of approximately $f/2.8$ for the same aperture. Curves A and B represent two members of a family, any one of which can be used. They differ chiefly in magnification. Curve A has no magnification. Its center is perfectly flat, and its curve is approximately a fourth-degree paraboloid. Other possible curves may be thought of as curve A superimposed on convex spherical surfaces of various curvatures. Because of the importance of reducing chromatic aberration to a minimum, it is advisable to choose curve B, in practice, rather than any of the other possibilities, especially when the focal length is very short. It is to be noted that this curve has a positive slope at the edge, equal to the negative slope at a point nearly half way out from the

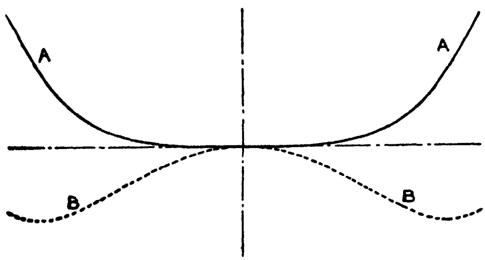


FIGURE 3

center, and this slope is only half as great as at the edge of curve A. It will also be noticed that a neutral zone, where the front and back of the lens are parallel, occurs at approximately 0.87 of the radius of the lens out from the center.

These correcting lens curves represent variation in the thickness of the glass. Theoretically the variation should be divided between the front and back surfaces about in the ratio of 3:1 for minimum chromatic aberration, but in practice there is no need for such ultra-refinement. The back may be made optically flat or *very* slightly spherical, and the front figured to obtain the right variation in thickness. With good luck a piece of ¼″ plate glass might be selected, suitable for a small correcting lens, but a disk of low dispersion optical crown would usually be better. With the longer focus aplanats, such as Example II (to be given presently), the grinding and polishing can perhaps be done by conventional methods, but the curves are so extreme with short focus ones that much of the figuring must be done by local fine grinding. A spherometer is a handy thing to use in this work and it is not difficult to make a good one. With this mounted on a sufficiently large rigid tripod, one can place the lens on a large flat plate of glass and

use the spherometer with its three legs on the flat plate and its measuring screw over various zones of the lens, in order to ascertain the figures within a few ten thousandths of an inch.

It is possible to make a usable camera with no more exact theoretical information than has already been given. But, with such short focus affairs as these aplanats are likely to be, it is advisable to follow the mathematical theory closely. Then an instrument at least equal in performance to the finest lens camera made is within the bounds of possibility. Fundamental formulae for lens thickness and mirror shape will first be given to a considerable degree of accuracy, since all other formulae needed are derived from these. The meanings of the symbols used will be made clear by referring to Figure 4, where all quantities are positive as drawn except s. F is the equivalent focal length of the telescope. The distance M from mirror to focus will generally be slightly less than F, because of the slight convexity

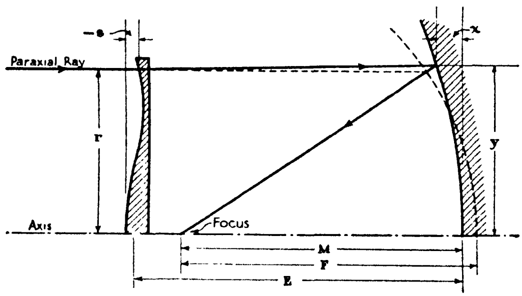


FIGURE 4

of the central parts of the lens. E is the "equivalent air path" from front of lens to mirror. That is (assuming that the back of the lens is practically flat) E equals $1/n$ times thickness of lens plus distance from back of lens to center of mirror, where n is the index of refraction.

The thickness of the lens at any zone of radius r minus the thickness at the center is

$$s = -\frac{(F - M)r^2}{2(n - 1)E\,F} + \frac{M\,r^4}{16(n - 1)E\,F^3} + \frac{(4E + F)M\,r^6}{192(n - 1)E^2\,F^5} \ldots (1)$$

The depth of the center of mirror below any zone of radius y is

$$x = \frac{[E - (F - M)]y^2}{4\,E\,M} + \frac{[M - (F - M)]y^4}{32\,E\,M^3} + \frac{(E + M)M\,y^6}{384\,E^2\,M^5} \ldots (2)$$

Except that slight approximations have been made in Equation (2) for the sake of simplicity, these formulae are essentially the same as those derived by Schwarzschild for two-mirror aplanats. For such types the

formula for the large mirror can be obtained by substituting $n = -1$ in Eq. (1), and for the small mirror

$$x = \frac{[E - (F - M)]y^2}{4\,EM} + \left\{\frac{M - (F - M)}{E} + 2\left(\frac{F - M}{E}\right)^2\right\}\frac{y^4}{32M^3}\cdots$$

The curves in Figure 3 were calculated from Eq. (1). For curve A $(F - M) = 0$, so that $F = M$, but for the preferred curve B the value of $(F - M)$ is computed from

$$F - M = \frac{3k^2}{64}[1 + 0.08\,k^2]F \tag{3}$$

where k is the ratio of lens aperture to F. However, it is nearly always close enough to compute $F - M = 3k^2F \div 64$.

A general formula can be derived from Eq. (2) for figuring the mirror for a telescope having any suitable values for F, M and E. But it will simplify matters to consider separately the Schmidt and the "short" telescopes. For the Schmidt telescope Eq. (2) reduces to that of a sphere when $E = F + M$, and in this case the radius of curvature of the surface is also $= F + M$. After deciding on the desired value for F, the procedure in the case of a Schmidt telescope is to calculate $F - M$ from Eq. (3), then subtract this from F to obtain M. The mirror is then figured as closely as practicable to a sphere of radius $F + M$. After completing the mirror, its radius of curvature should be carefully checked and the values of F, M and E revised to harmonize with the measured radius. Usually the difference $F - M$ can be allowed to remain as originally calculated. These revised values should then be substituted in Eq. (1), as a guide for grinding the correcting lens as close to the ideal form as practicable. The finished lens should be mounted so that the distance from mirror to back (plane) side of lens equals the radius of curvature of the mirror minus ⅔ times thickness of lens (assuming $n = 1\frac{1}{2}$).

For the "short" telescope, after deciding on a value for F and also a value for E, either equal to or somewhat greater than F, Eq. (3) is used to calculate $F - M$, which is subtracted from F to obtain M. The mirror is then ground to a sphere of radius R_0, given by the formula

$$R_o = \frac{2\,E\,M}{E - (F - M)} \tag{4}$$

When the polishing and figuring are finished the radius of curvature R of any zone of radius y should conform to the formula

$$R = R_o - \left(\frac{2\,M - E}{E}\right)\frac{y^2}{2\,R_o} \tag{5}$$

In deriving this formula from Eq. (2) some approximations have been made in the smaller parts, in order to make the formula as simple as practicable. It is sufficiently accurate when E differs from F by not more than 10 percent

at aperture ratios of about $f/3$ or longer. A more elaborate formula would be necessary to cover other possible cases.

Formula (5) is just as simple to use as the corresponding knife-edge testing formula $R = R_o + \frac{y^2}{2 R_o}$ for a paraboloid. Knife-edge and light source move together in applying any of the testing formulae given in this chapter, and the computed movement of the knife-edge should be doubled when the light source is to remain fixed. After the mirror is figured according to Eq. (5) the radius of curvature R_0 is carefully measured and the values of F and M adjusted accordingly. Usually the values of E and $F - M$ can be left unchanged, and F and M can each be changed by half the change in R_0. The revised values may then be substituted in Eq. (1), to ascertain the profile of the correcting lens for comparison with actual spherometer measurements.

Following are typical examples of Schmidt and "short" telescope design. It is assumed that $n = 1.52$. All dimensions are expressed in inches.

Example I: An $f/2$ Schmidt telescope of 8″ aperture. Mirror should have about 12″ diameter for 2″ photographic films. $F = 16$, $F - M = 0.1913$, $M = 15.8087$, $E = 31.8087$ and mirror is figured spherical to this radius of curvature.

Example II: An $f/4$ "short" * telescope of 8″ aperture. Mirror should have about 10″ diameter for 2″ photographic plates or films. $F = 32$, $F - M = 0.0942$, $M = 31.9058$, $E = 34$.

zone (=r or y)	Variation in Thickness of Lens (= $-s$)		Zonal Variation at Center of Curvature for Example II	
	Example I	Example II	For Testing Mirror	For Testing Lens
0	0	0	0	−.355
0.5	.00009	.00002	−.002	−.347
1.0	.00035	.00008	−.007	−.325
1.5	.00074	.00017	−.016	−.289
2.0	.00121	.00028	−.028	−.237
2.5	.00168	.00039	−.043	−.171
3.0	.00206	.00047	−.063	−.090
3.5	.00220	.00050	−.085	+.006
4.0	.00196	.00044	−.111	+.116
4.5			−.141	
5.0			−.174	

Lower describes a convenient method he has discovered, of testing the lens with a slit source placed at the focus of the telescope. This could also be used for a "short" telescope, but the length of the slit must be at least equal to the aperture of the lens, times the ratio of focal length to distance be-

* Shall this be called the Wright camera?—*Ed.*

tween lens and observer. This test, in its simplest form, is probably not sensitive enough for the final figuring of an $f/4$ telescope. However, light coming from the slit image to the eye can be caused to pass between an accurate straight-edge placed close in front of the lens on one side and a movable knife-edge close to the eye on the other side of the beam, both of them being adjusted parallel to the slit source. Knife-edge and the observer's eye are moved slowly sidewise until the slit image starts to disappear behind the straight-edge. At this point the slightest deviation in the rays would cause part of the slit image to vanish, while the rest would still be

FIGURE 4

The author. (The observatory in the background is the same one shown in Scanlon's chapter on observatories, Figure 5.)

visible. The same test could be performed without the knife-edge, although it would probably not be quite so sensitive.

Since a "short" telescope would generally be made with a long enough focus to use a diagonal flat or prism, like a Newtonian, it could readily be tested at focus with a knife-edge or grating, using Ritchey's or any method for feeding parallel rays into the telescope. Another method for testing the correcting lens, applicable to "short" telescopes of around $f/3$ or longer, is to set up the mirror, which has already been figured for the same telescope, for a knife-edge test at its center of curvature. For any given zone the position of the "apparent" center of curvature, with and without the cor-

recting lens placed against the mirror, is obtained. The lens should be well centered over the mirror, but may be tipped up enough to prevent extraneous reflections from its surfaces from entering the eye. The difference between these two points should be in accordance with the formula

$$-\frac{4\,F(F-M)}{E}+\frac{r^2}{E} \tag{6}$$

This is accurate to within 0.005″, in the case of Example II, for which the results are given in the last column, but should not be used in cases where E differs from F by more than 10 percent. It is to be noted that this test is independent of the accuracy of figure on the mirror. The displacement of the focal point, due to the lens, is toward the mirror near the center where the formula gives a negative value, and away from the mirror near the extreme edge, passing through zero displacement at the neutral zone. In an $f/4$ telescope the amount of convexity at the center of the lens, as determined by the first term in this formula, is not at all critical, and may even equal zero without causing noticeable chromatic aberration. But it is important that the difference in results from zone to zone should vary closely according to the r^2/E part of the formula. However, there is twice as much tolerance here as in figuring the mirror itself with tests at the center of curvature.—*155 Bret Harte Road.*

Notes on the Construction of an F/1 Schmidt Camera

By Harold A. Lower
San Diego, California

The Schmidt camera, being free from astigmatism and coma, may be constructed in very short focal ratios, and will give sharp definition over a much wider field than is obtainable with reflecting cameras of the Newtonian type. For example, it is entirely practical to construct a Schmidt camera of $f/1$ which will cover a field of 20°. Such an instrument should be very useful for meteor photography and for the mapping of areas of faint nebulosity, as such work requires not only a fairly large aperture to gather the necessary light, but a very short focal ratio, in order that the light may be concentrated in a small, bright image.

The design of a Schmidt camera is beautifully simple, as it makes use

Figure 1

of a spherical mirror, which is the easiest of all optical surfaces to make accurately. A correcting lens which is located at the center of curvature of the mirror is figured to a complex curve which corrects the spherical aberration of the mirror. The surface of best focus, which is located midway between the lens and mirror, is convex toward the mirror, with a radius of curvature equal to the focal length.

In order to determine the practicability of an instrument of extremely short focal ratio, we decided to attempt the construction of a Schmidt camera of 8″ aperture, with a focal ratio of $f/1$. This required a 12″ mirror with a radius of curvature of 16″. A suitable Pyrex blank was obtained and was ground to the required curve, 98 hours, and 25 lbs. of Carborundum being required for the roughing out. When the mirror was fine ground and polished (Figure 1), difficulty was encountered in testing, as we found

that the usual method of offsetting the light source from the optical axis, in order that the returning beam might reach the eye, was not satisfactory. Due to the extremely high aperture ratio of the mirror, the slightest departure of the cone of light from the optical axis produced astigmatic effects which caused the mirror to appear warped. To overcome this, the light source, a vertical slit, was reflected to the mirror by means of a small, unsilvered diagonal mirror, the returning beam passing *through* the glass to the eye. By this method, both the light source and the eye can be exactly on the optical axis, and astigmatism is entirely avoided. As it was found impossible to obtain uniform illumination over the entire mirror, the knife-

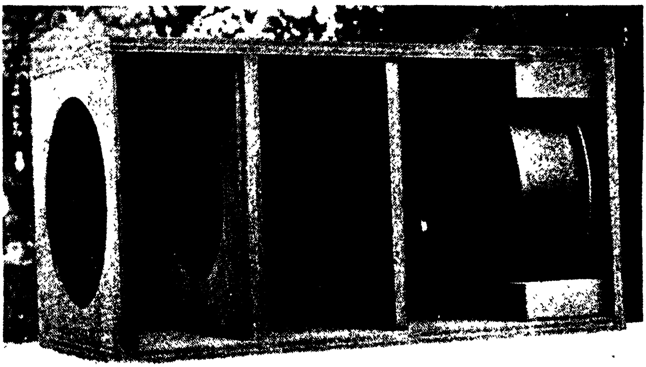


FIGURE 2

The interior of the camera mentioned in the text. Made by Charles A. and Harold A. Lower. Note the stops, also crossed strings for help in collimating. The collimation is a tedious job, and the least change makes a big difference on the plate. Check-ups after each change must be made photographically.

edge method of testing was discarded in favor of the Ronchi test, which proved entirely satisfactory.

Having completed the mirror, the next problem was the making of the correcting lens. There are several different curves which may be used to correct spherical aberration. All of the correction may be on one side of the lens, leaving the other surface plane, or the correction may be divided between the two surfaces. The curve may be concave or convex, or a combination of the two. In the case of our camera, we decided to make all of the correction on one surface, and to use a combination of concave and convex curves, as this type of lens would have less chromatic aberration than if one of the other curves was used. It is obvious that a complex curve of this kind cannot be ground with a full-sized tool, and as the radius of curvature is constantly changing as one passes from center to edge, even small tools must have a certain amount of flexibility. To obtain this flexi-

bility in a grinding tool, a sponge rubber base was used, and the grinding surface was made up of ½″ squares of single strength window glass, cemented to the rubber with pitch. This method was first employed by Dr. H. Page Bailey, of Riverside, California. Several different sized tools were used, ranging from one 5″ in diameter, down to one so small that only two ½″ squares of glass were used on it. Polishing also required flexible tools, and sponge rubber surfaced with beeswax proved fairly satisfactory. All grinding and polishing was done on a machine. In order to be able quickly to remove the lens from the machine for testing, and replace it in the same position for additional work, the lens was cemented into a ring of Bakelite

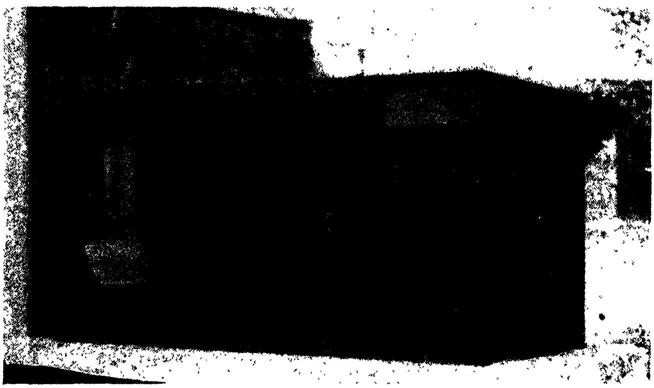


FIGURE 3

Another view of the interior of the 8″ Schmidt camera, during construction.

which could be screwed fast to the turntable of the machine. This left the back of the lens free of obstruction when testing.

It is quite obvious that the focal point of an 8″ *f*/1 Schmidt camera is not accessible to the eye, so the usual testing methods which are applicable to reflecting telescopes cannot be used for checking the figure of the correcting lens. However, a new and simple method of testing was devised which enables one to figure the correcting lens to the proper shape. This new test is similar to the Ronchi test, but no grating is required. The mirror and lens are set up in the same relation to each other which they will occupy in the finished instrument, and a light source (vertical slit) is placed at the focus, facing the mirror. The position of the light source is determined by measurement, and should be at the *infinity* focus of the camera. However, as this cannot be determined exactly until the lens is finished, it is sufficient for the purpose if the light source is located half the radius of curvature distant from the mirror. The light is reflected from the mirror, and passes through the lens. If the lens is correctly figured, the light should

leave the lens as a parallel beam, and if the eye is placed in the center of the beam, at a distance of 20′ or more, an image of the slit will be seen. If the eye is exactly in the center of the beam, this image will be a bright vertical line of light, perfectly straight, extending from top to bottom of

FIGURE 4

The finished job, with 7″ guide telescope and finder; also, at the base, a housing for a drive. The object on the strut attached to the polar axis is a 42-pound counterweight. Polar axis made from banjo type rear axle housing, with ends cut off and heavy shafting brazed in and turned down to 1½″ for bearings. The cast disk to which the camera is bolted forms a thrust bearing 8″ wide. The mounting, weighing 300 pounds, is portable and will be used in the mountains, away from city lights.

the lens, exactly crossing the center of the lens. When the eye is moved toward the edge of the beam, the line of light will move toward the edge of the lens. If this test is tried before the lens is figured, when the eye is moved toward the edge of the beam, the line of light will curve, showing

that spherical aberration is present, but if the lens is correctly figured, the line of light will remain perfectly straight as it moves from center to edge of the lens. The position of the observer is not important, except that it should be far enough from the camera for the line of light to reach from

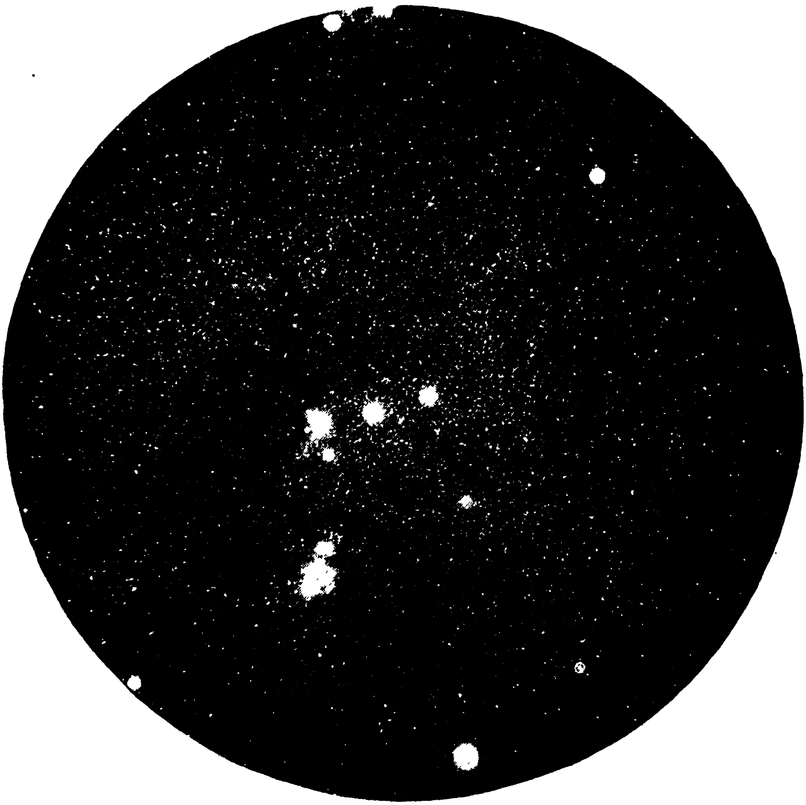


FIGURE 5

Central portion of the constellation of Orion, photographed with the camera shown in Figure 4. Exposure 10 minutes, January 19, 1936.

top to bottom of the lens, without having to use too long a slit. A slit 3/8" in length should be sufficient.

This method of testing is sufficiently sensitive to enable one to make a photographic instrument which will perform satisfactorily, but if greater accuracy is desired, after the lens has been figured until this test shows no

errors, a telescope of aperture at least as great as that of the correcting lens may be set up so as to pick up the beam from the camera and bring it to a focus. Then the knife-edge, or Ronchi, test may be used at the focus of the telescope, or the image of the slit may be examined with an ocular. Any errors shown by this test may be removed by figuring the lens, and there is no reason why the accuracy of figure cannot be carried to as high a degree as may be desired.

The curve of the correcting lens is entirely too deep to be figured by rouge polishing alone, and as it is difficult to measure a ground surface with sufficient accuracy, each spell of grinding must be followed by about an hour of polishing, in order to apply optical tests. Fortunately, the line of light used in testing appears quite bright, so an hour of polishing will make a lens ground with 2F Carborundum sufficiently transparent for a test.

As the focal surface of a Schmidt camera is not flat, but is a spherical curve, convex toward the mirror, with a radius of curvature equal to the focal length, it is obvious that glass plates cannot be used. However, it has been found that film can be sprung to quite a sharp curve by means of a ring which presses the film against a convex base. Thin film, such as the ordinary roll film, is not suitable, as it will wrinkle at the edges, but the heavier cut film can be sprung to the required curve, and when removed from the holder will spring flat again.

Test photos made with this camera and with an $f/4.5$ lens indicate that when exposures are calculated on the f ratio, with no allowance for the obstruction caused by the film holder of the Schmidt, the efficiency of the Schmidt is greater than that of the ordinary anastigmat lens. Evidently loss of light due to obstruction by the film holder is less than the loss caused by absorption and reflection in a lens of the ordinary type. These tests were made on illuminated surfaces, and not on stars, where the aperture and not the focal ratio would have been the controlling factor.

For astronomical work, we have found that sky fog limits the exposure to a maximum of 20 minutes, even on very good nights. However, long exposures are not necessary, as is proved by the amount of faint nebulosity shown in the Orion photo. The resolving power for faint clusters exceeded our expectations.

The construction of an $f/1$ Schmidt is a *slow* job, and should not be attempted unless one is equipped with a grinding machine and unlimited time.—*1032 Pennsylvania Street.*

Addendum: We all know that a parabolic mirror produces a perfect image when the incident light strikes it squarely, as at *A* in the left-hand drawing of Figure 6. Now suppose we place a diaphragm at the center of curvature, and arrange our mirror so that it can swing about the center of

curvature, in such a manner that it always faces squarely toward the incident light. Such a perambulating parabola could build up an image at *F* that would be free of all aberrations. It is obvious that this image surface would be convex toward the mirror and would have its center of curvature at *C*.

As a spherical surface is the only one which will always appear symmetrical to light passing through its center of curvature, regardless of its direction, it is impossible for us to use a parabolic mirror. However, we may place a lens at *C* which will produce the same effect on the light as if we parabolized our spherical mirror. Now, as the correction is applied to the light, and not to the mirror, we have the same effect as if the parabolic correction were able to slide around over our spherical mirror in such a manner as always to face squarely toward the light.

This enables us to produce an image which is free from coma and spherical aberration. There is a small amount of astigmatism near the edge of the field, which is caused by our being unable to have the *lens* face squarely toward light which enters at an angle.

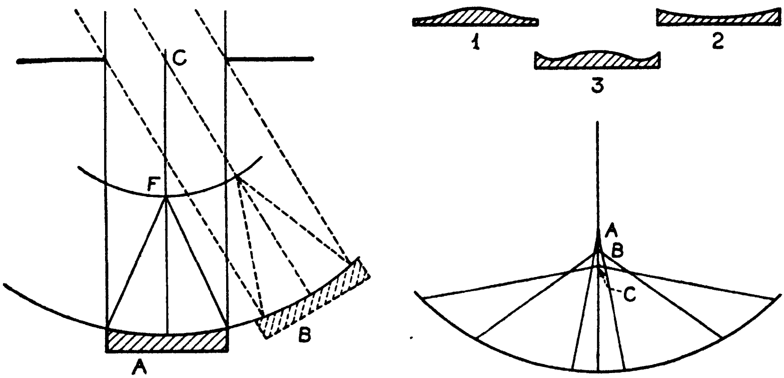


FIGURE 6

In case it seems strange that the figure of the correcting lens may have any one of a number of different shapes, we should remember that we can parabolize a spherical mirror in several different ways. If we parabolize by shortening the radius of the central parts, we merely shorten the focus of rays *A* and *B* (lower, right) until all rays focus at *C*. Lens No. 1 (upper, right) produces this effect by causing the central rays to converge more rapidly, but leaves the edge rays unaffected. We could also parabolize a spherical mirror by lengthening the radius of the edge zones. This would lengthen the focus of the edge rays until all rays would meet at *A*. Lens No. 2 produces this effect. Another way to parabolize is to shorten the radius of the central parts, and lengthen the radius of the edge zones of our mirror. This would cause all rays to meet at *B*. Lens No. 3 produces this effect.—*H. A. L.*

The Camera Obscura

By Horace E. Dall,
Luton, Bedfordshire, England

[Editor's Note: Before reading the chapter which follows, a rough preliminary explanation of the drawing, Figure 1, which Russell W. Porter has made from a rough sketch furnished by the author, may prove helpful. At the top is a flat which may be moved both in azimuth and altitude. The rays of light from the field, either terrestrial or celestial, are reflected straight downward by this flat and pass through the O.G., which is fixedly mounted a few inches below it. The image is formed some feet below, on a viewing table in the attic room. The observer is shown looking at the image on this table, but if he prefers to do so he may draw over toward him the viewing telescope, which looks something like a microscope (there is no absolute demarcation between a telescope and a microscope) and see small details in the image more highly magnified. The other large drawing, Figure 2, was also made by Porter, from a detailed rough sketch furnished by Mr. Dall.

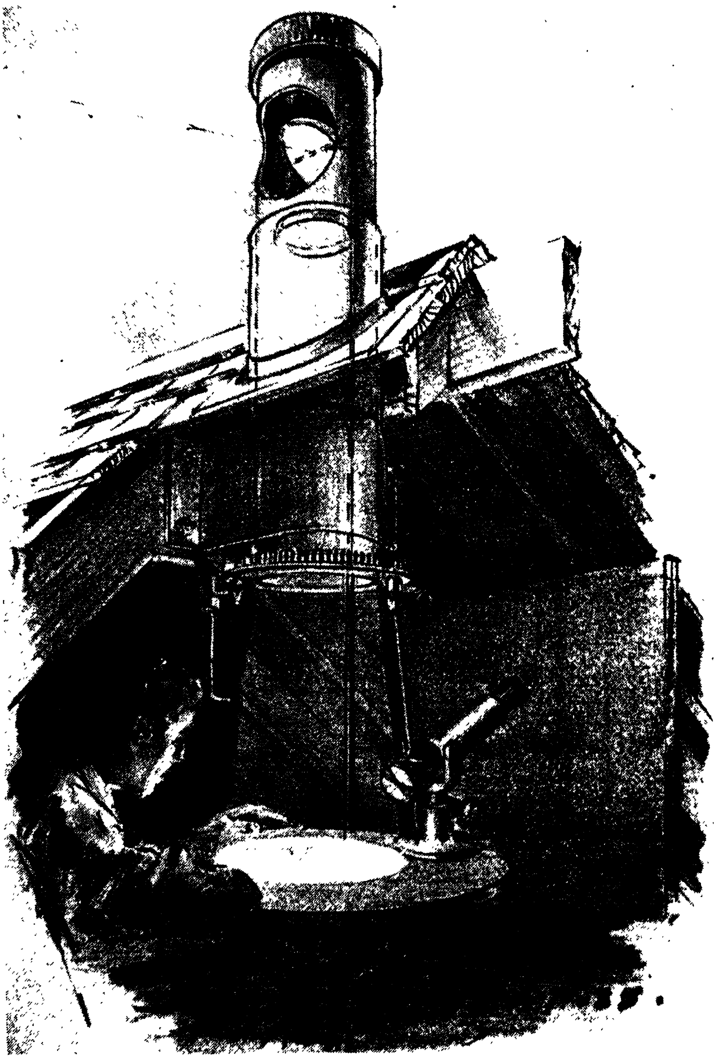
Mr. Dall first described his obscura in a letter to the editor. Later, when the present volume was being prepared, it was thought that it would be better in every way simply to present that letter just as it was written, instead of attempting to "work it over" into conventional form. It follows.]

"I am very bucked with my camera obscura, just finished.

"I told you that the object glass was unusual. Personally I have never heard of coincidence of focus for four colors of the visible spectrum with only two components—consequently I don't see any false color even on Venus, and my old grudge against the refractor is wiped out.

"The viewing table is 2 feet in diameter and I can turn the handle and show over a hundred different views—full of life and color of the surrounding landscape and townscape. Up to an altitude of 40° I can get any part of the sky—unobstructed; which means that the sun is observable nearly any time I want to see it. Sitting in a comfortable chair in the dark I project a 6 foot solar disk on to a screen—full of detail—granulations, faculae and spots. There is enough light for a projection on a scale of 22 feet to the solar disk and a sunspot group a foot or two long sails majestically across the screen. The flat mirror above the O.G. has to be unusual in accuracy (flatter than $1/10^{6}$") to pass on without visible error rays for such a long focus beam. The viewing telescope is arranged at a comfortable microscope angle 45° downwards—no neck aches here. The lowest power eyepiece, $\times$ 48, has a field lens 2½" in diameter. Rack focus on both table and viewing telescope, and rod controls from up aloft.

"A little novelty tried with it recently: I projected in the dark a microscope slide of a flea (using the camera obscura like a projecting microscope), with a magnification of 500, on to a screen rigged up by a friend in a village over a mile away from here. Does this suggest possibilities to you? Anyway it's good fun."



Drawing by Russell W. Porter

FIGURE 1

The drawing is compressed. Actually the tube is 9' above the table top.

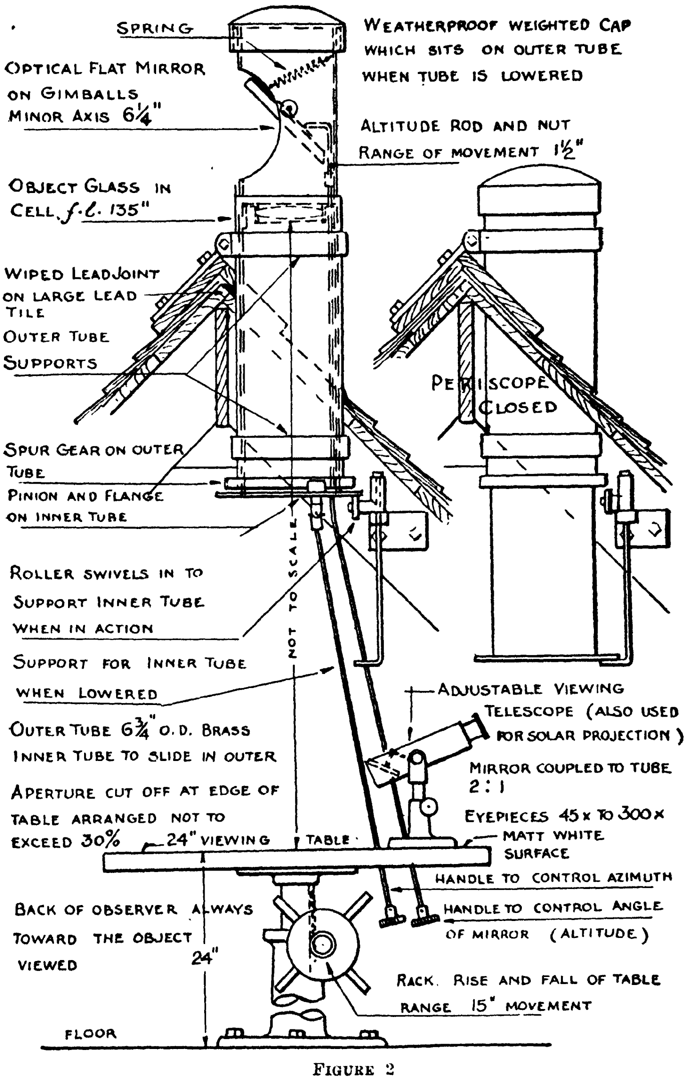

SPRING
WEATHERPROOF WEIGHTED CAP WHICH SITS ON OUTER TUBE WHEN TUBE IS LOWERED
OPTICAL FLAT MIRROR ON GIMBALLS MINOR AXIS 6¼"
ALTITUDE ROD AND NUT RANGE OF MOVEMENT 1½"
OBJECT GLASS IN CELL. f.l. 135"
WIPED LEADJOINT ON LARGE LEAD TILE
OUTER TUBE SUPPORTS
PERISCOPE CLOSED
SPUR GEAR ON OUTER TUBE
PINION AND FLANGE ON INNER TUBE
ROLLER SWIVELS IN TO SUPPORT INNER TUBE WHEN IN ACTION
NOT TO SCALE
SUPPORT FOR INNER TUBE WHEN LOWERED
ADJUSTABLE VIEWING TELESCOPE (ALSO USED FOR SOLAR PROJECTION)
OUTER TUBE 6¾" O.D. BRASS INNER TUBE TO SLIDE IN OUTER
MIRROR COUPLED TO TUBE 2 : 1
APERTURE CUT OFF AT EDGE OF TABLE ARRANGED NOT TO EXCEED 30%
EYEPIECES 45x TO 300x
24" VIEWING TABLE
MATT WHITE SURFACE
HANDLE TO CONTROL AZIMUTH
BACK OF OBSERVER ALWAYS TOWARD THE OBJECT VIEWED
HANDLE TO CONTROL ANGLE OF MIRROR (ALTITUDE)
24"
RACK. RISE AND FALL OF TABLE RANGE 15" MOVEMENT
FLOOR

FIGURE 2

[EDITOR'S NOTE: Asked to provide more explicit details regarding the method of projecting the flea—at least the flea's image—the author wrote: "Any optical system is reversible in the sense that if a self-luminous object is placed in the normal image plane, an image is thrown toward the normal object plane. In the flea projection, an illuminated microscope slide becomes the self-luminous object. The light-source is an arc lamp (a car bulb—12 v., 48 w., or 6 v., 24 w.—can be used, but of course the intensity will not be so good as with an arc). The arc is placed within an enclosure having an opening, behind which is a condenser lens of short focus, to fill the O.G. with light. The arc lamp is placed at one focus, the O.G. at the other. In front of the enclosure is the micro slide with the flea or what-have-you. Next comes a flat or a prism, turning the light directly upward to the O.G. If the projection distance is 1 mile, the image thrown will be as many times full size as the focus of the O.G. is contained in a mile (In my case, × 480, and the flea shows about 4′ long). The novelty with this method of projection lies only in the *distance*, and the fact that the O.G. has such an unobstructed outlook. The same kind of projection or signaling can, of course, be done with any telescope, especially if of long focus, but it is not generally so convenient as with the camera obscura. I have projected slides of written messages in the same way, and as the field is so confined in size, even the next door neighbor of the collaborator two miles from the camera obscura doesn't see the light." Mr. Dall's method is suggested for various practical uses—for example, down the block a youthful couple is known to be sitting in a cozy, dark corner on a porch. A message—for example, "Watch your step!"—suddenly appears on the side of the house above the sofa. Variants will suggest themselves.]

A second letter from Mr. Dall follows:

"You ask for more data about my camera obscura, also Porter seems not to be familiar with them.

"Well, if you saw the view of a sunny landscape pictured by mine—full of living detail and brilliant with colors, *apparently* more vivid than the colors of nature itself, because the observer's eye is not flooded with sky light, I think you would vote the C.O. a marvelous optical invention. Not a recent invention, either. I have an ancient English book of popular science, dated 1848, describing one of a sort.

"At English seaside resorts they are not uncommon, and for a charge of tuppence one enters the dark interior of a tall tent-shaped hut—generally on the pier or other high spot—and gets a fascinating and highly magnified view of the seething life on the sands, and around the whole 360° of the viewpoint up aloft.

"The scene glides across the table in endless panorama as the control rods are operated. The seaside variety merely needs a lens and mirror housing but no tube. In my case I have a house on top of a hill, some 200 feet above the valley level, and higher than practically any house in the vicinity.

"My loft is boarded and forms a useful room with a 20-odd feet-square

floor. A 5′6″ × 3′, 3-section window is in one end but can be covered in a few seconds by a hinged screen—lightproof.

"As I wanted to get a viewpoint well clear of the roof ridge, I had to poke a hole through the roof and insert a fixed tube, inside of which slides an inner tube carrying the optical items.

"The main items of the layout are shown on the rough sketch attached [the elevation drawing, as redrawn by Porter—*Ed.*] which, if you read the various items noted, becomes self-explanatory. The O.G. forms an image of external objects to which the mirror is directed, and throws it on to the viewing table. Ten degrees diameter (say nearly 80 square degrees) at any one position of the mirror, is seen on the table, and if you look at the table from a distance of 10″, the effective magnification of the view is 135″/10″ = 13½ times. If a short-sighted person looks from 5″ distance the magnification becomes ×27. Not only do you get good magnification, but the field of view is extensive. Three or four of us can get a "tabular" view of a cricket match nearly one-half mile away and not miss a ball. Ditto tennis—quite a number of courts are in view from 150 yards away and upwards.

"Now, if you want to see anything in greater detail and higher magnification, you apply the viewing telescope and observe in great comfort a very brilliant image. The viewing telescope is somewhat like a microscope without an objective, and with a body large enough to take the lowest power eyepiece—in my case a fine Huygenian of about 3″ focus and 2½″ field lens (1° actual field, 45° apparent). Rack focusing and swivelling bracket add to the comfort. The image is much more brilliant than the same aperture would give with a telescope used in normal terrestrial fashion, because 'visual purple' is secreted on the retina in the dark.

"Although the O.G. works at *f*/32 (4¼″ aperture in my case) anyone familiar with the ground glass screen view of a camera at *f*/32 might think the image would be too feeble. This is not so, because of the sensitivity of the observer's eye under such ideal conditions.

"Of course, if the day is dull or the sun on the horizon, the landscape image on the table is not so bright as one would like. Incidentally a beautiful sunset (or sunrise!) seen on the table is a thing not to be forgotten in a hurry. The solar image is 1¼″ diameter and is a great sight, toned down by the horizon vapors.

"The whole panorama of the horizon is 70 feet long, and as one sweeps the horizon across the table by operating the azimuth control, so must the observer move round the table to keep his back toward the object viewed, if the top is to be at the far side of the table. If looking at the moon (usually with the view telescope), face the direction of the moon, if you want to see it astronomically inverted, and put your back toward it if not. Of course, it is only a mechanical addition to have a rotating floor operated automatically, if you feel badly in need of it! For astronomical purposes, as I have said in my last letter, solar projection is ideal. I tilt the view telescope nearly horizontal and use a 4-lens, achromatic eyepiece, giving me a 6-foot solar disk on a vertical white screen 7 or 8 feet away. Granulations of the surface,

together with spots and groups in great detail, (also faculae), make a great sight for an observer who has struggled to get a decent view through a dusty cracked sun glass (not that I am including myself); or who has managed a milky, flooded projection about 6″ across on a rickety rig-up threatening to sag the eye-end earthward. Instead of a view on the horizontal table—a somewhat brighter ground glass view can be obtained using a ground glass and mirror in a frame on the table. In either case the view is companionable—several people can see at the same time, but not with the viewing telescope.

"Of course anything can be photographed with ease—the operator is inside his own camera. With an infra-red filter, etc., I am hoping to get some good views of distant items, like churches in wooded surroundings 17 miles away. One is naturally dependent to some extent on atmospheric steadiness for the telescopic or photographic view. I don't seem to have been much worried by hot air off the roof, but a sunny day is never any too good for telescopic views of landscape, except in the evening or perhaps the early A.M. if you are energetic. A whitened roof would be all to the good, but I haven't whited mine.

"In addition to the 70-foot horizon strip there is of course the 70-foot strip above or below—several of them, each side—glorious views of scudding cloud in blue sky—curdled thunder clouds, or "mackerel," in addition to quite a new world of cloud color in the refractive zone of a solar halo of cloud water particles.

"I have only 4¼″ aperture, but remember that I have aimed at getting as near to optical perfection as I can achieve. I chose a pair of Chance Bros. melts—a hard crown and a special telescope flint, the crown having a μ_D of 1.515 and the telescope flint only 1.530 (approx.), which enabled me to get what is, for me, an unheard of coincidence of focus for four colors of the visible spectrum, viz., h, F, D, and C. The quatenary spectrum left over is less than a tenth of the usual secondary spectrum of a normal flint and crown doublet, and to ordinary observation, astronomical or terrestrial, false color is non-existent. The other night I was looking at the moon—as hard and colorless on the edge as with a reflector—and I could *just* see the twin craterlets inside Plato.

"A long focus enables this high color correction to be achieved without absurdly deep curves, but naturally the surface accuracy needs to be very good and the mirror above superlatively so if the image is to be at its best possible. A silvered-back, plano-parallel mirror in optical glass is a teaser, and is probably not worth the trouble in these days of aluminizing.

"There is nothing in the outfit beyond the scope of the advanced amateur —but if the A.A. has his house tucked in a valley or between high chimney pots, there won't be so much attraction. I don't see much need to go into minute details of my construction—any advanced amateur prefers to settle details himself to suit his own available means. My sketch, plus all notes lettered on it, plus this letter and the last, ought to suffice for you to put out a new idea in optical equipment, at least, let us say, a rehash of an old

idea. Ever since I got into this house (and I got it built rather tall with this in mind) I have hankered to have a periscopic type of view. I started in May, and was viewing in early July—but of course it was only one of several other odd sparetime jobs. I have yet to add refinements like azimuth and altitude scales, shutters for photograph, photo projection lenses for enlarging the image, screens, etc., etc.

"Was it in my last letter that I told you about my projection game? It

The author, looking down into the Hjelle Valley while on a trip in Norway. "Not contemplating suicide" is the comment he wrote on the back of the original.

was funny to project the image of a flea on the side of a house a mile away —well the camera obscura did this and I have done other signaling with it— it wouldn't be difficult to arrange to talk via light ray to a distant friend—any A.A. could think out fascinating side lines or stunts for his amusement similar to these. You get strings of friends along to see the view.

"I hope you can cull together something on the camera obscura by way

of the sketch, this, and my two previous letters."—*166 Stockingstone Road.*

[EDITOR'S NOTE: Asked for data about the eyepiece used in the viewing telescope, the author later wrote: "Re. eyepieces, nothing really out of the way. With the Huygenian, add the specification, if you like:

Field lens F = 5.0", dia. 2.5" } Separation 3.5", plano-convex, borosilicate
Eye lens F = 2.25", dia. 1.25" } crown or dense barium crown
Diaphragm aperture dia. 1.85"

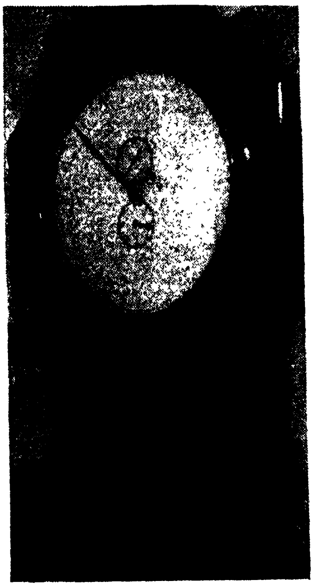
"Owing to the large F number, the color and spherical troubles of Huygenian eyepieces do not affect the camera obscura view. For projection, however (as for solar projection) the eyepiece to be used must be *fully* corrected. If a Huygenian were used for projecting the sun, color fringes, while they might please the unscientific visitor, would be pretty hopeless.

"Re. the O.G., I used the Fraunhofer type for the O.G., on account of the better definition away from the center. This type has a convex back (see Bell, 'The Telescope,' p. 37) and has three convex curves and one concave. It is no use giving actual curves, because these will depend *enormously* on the actual glass selected. No two melts are enough alike in this range. The method of calculating follows generally that given in 'A.T.M.' I cement the pair together to avoid all avoidable losses. The inner tube carrying the O.G. should be lined or threaded internally to stop wall reflexions."]

Converting a Seth Thomas Clock into a Sidereal Clock

By John Bunyan
Berthoud, Colorado

A weight-driven Seth Thomas clock with seconds pendulum was purchased. The gear was changed to make the hour hand revolve once in 24 hours and this hand was brought down on a dial of its own, below the center of the main dial. A new pendulum was constructed, using a steel rod and a mercurial bob consisting of two test tubes supported in a suitable frame. This pendulum is quite accurately adjusted for temperature and the clock has been regulated as close as a second a week. The barometric error, of course, is not corrected. The clock dial is of heavy paper and the circles and figures were drawn with india ink.



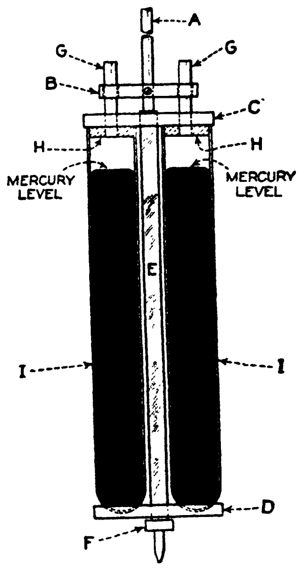


Figure 1

The clock is checked by U. S. Naval Observatory short wave time signals, after having first converted civil time into sidereal time by means of tables in the American Ephemeris. It is checked at times by direct observation of the transit of stars with a small meridian telescope.

In Figure 1, *A* is a $\frac{3}{16}''$ steel rod with total length of 45″, including a flat suspension spring at the top.

B is an aluminum cross bar 2″ long, $\frac{7}{16}''$ wide, $\frac{1}{4}''$ thick. *A* runs through

its center and a set screw keeps *B* from turning on *A*, holding the bob in alinement with the swing of the pendulum.

C is an aluminum cross bar 2⅝″ long, 1$\frac{3}{16}$″ wide, ¼″ thick.

D is an aluminum cross bar, the same size as *C*.

E is an 8⅜″ length of square brass tubing, with ¼″ internal diameter. It passes through square holes in *C* and *D*. Set screws at back of *C* and *D* hold the parts together.

F is a knurled nut running on thread at bottom of *A*, to support the bob and for regulating the clock.

G-G are ¼″ brass rods 1½″ long, running loosely through *B* and held tightly in *C* and *H-H*.

H-H are aluminum disks ⅞″ in diameter.

I-I are glass (not Pyrex) test tubes 8″ long, with ⅞″ internal diameter, held in place by slipping over *H-H* and resting in countersunk holes in *D*. These test tubes are filled with mercury to a depth of exactly 7″.

The expansion of the steel rod downward is compensated by the expansion of the mercury upward (allowing for the expansion of the glass tubes themselves) so that the distance from the point of suspension of the pendulum to its center of gravity remains unchanged by heat and cold.

Before constructing the pendulum just described I tried out the original pendulum but did not secure nearly the accuracy I do now with a mercurial pendulum. A wooden rod is apparently affected to a greater extent by moisture and atmospheric dryness than it is changed by heat or cold. A very full discussion of the mercurial pendulum is found in the eleventh edition of the Encyclopaedia Britannica, under the article "Clock," and the depth of the mercury in glass tubes is worked out.

A Precision Clock *

BY B. L. SOUTHER Ph.D.
Wexford, Pennsylvania

The Synchronome system of timekeeping consists of a master pendulum (Figure 1) and as many secondary movements (Figure 10) as desired. The former transmits electrical impulses to the secondary movements that record them, thus indicating the time.

The pendulum swings once in two seconds, operating a count-wheel (see Figure 3, "Wheel") during each excursion. This wheel is provided with 15 teeth and a projection on its axis which releases a pivoted weight once each revolution. As the weight swings gently against the pendulum, it imparts sufficient energy to it to keep it swinging for half a minute. At the same time an electrical circuit is closed, thereby causing two magnets to become energized, one resetting the weight and the other operating a secondary movement (Figure 10).

The rough castings for making the writer's clock were purchased from the Synchronome Company, Ltd., of London [32 Clerkenwell Road, London, E.C.1.—*Ed.*], as were also the three wheels for the secondary movement, the bobbins for the electromagnets and several pieces of soft iron for the magnet cores.

The clockmaker will require the following tools for constructing the clock: a screw-cutting lathe, a small vice, a drill press, drills (preferably two sets, a numbered set, 1 to 60, and another set 1/16" to 1/2" by 1/64"), files, small A.S.M.E. taps, especially sizes 2-56, 6-32, 8-32 and 12-24, a hack saw, a jeweler's saw, and a machinist's square. A small shaper is very convenient but not essential. The writer has a 7" shaper, the smallest size made, that is very useful for small work.

Figure 1 is a photograph of the completed master pendulum and its accessories. It should be studied with the aid of Figures 2 and 3, which show many of the details of the mechanism, before starting to make it. A back-plate of iron or steel, with two brackets at the top to support the pendulum, is used as a base upon which to mount the whole device. Back of the pendulum, the count-wheel and the auxiliary parts for resetting the pivoted weight are located. The length of the master pendulum is about 44", measured from the upper clamp-support to the lower end of the pendulum rod.

The Back-plate: A Synchronome back-plate was used for mounting the writer's pendulum. It was received as a rough casting and hence had to be cleaned. The posts that serve to hold the bearing plates also required surfacing. For the rough cleaning and the removal of any sand that may still

* This description of the Synchronome method of timekeeping has been written with the permission of Mr. F. Hope-Jones, the patentee. The dimensions of the parts of the transmitter have been taken from the book "Electric Clocks and Chimes." As the Synchronome Master Clock is patented, it may be made by the amateur for his own use alone, and not for sale.

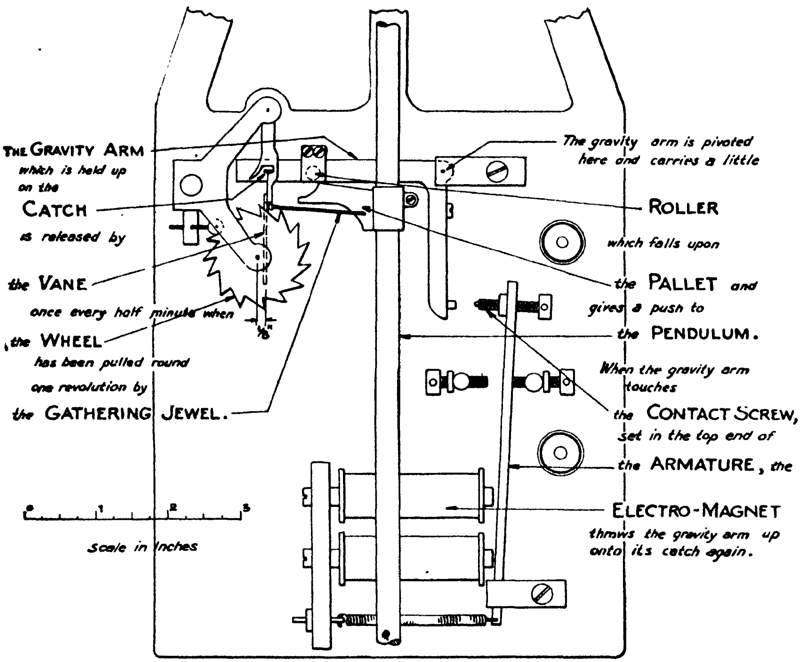
FIGURE 1

The author, with Mrs. Souther, showing the escapement of his precision clock. The secondary shows beneath the clock. (At the right is a portrait of the late "Uncle John" Brashear, famous character in the world of optics.)

FIGURE 2

be clinging to the casting, an old file works very well. A new file would serve no better and would soon be spoiled.

The tops of the brackets (Figure 4) should be trued with a file, or if possible planed in a shaper. Four holes are then drilled and tapped 8-32 A.S.M.E. to hold the clamps in place. The necessary dimensions are given in the figure with which, as with all the other separate drawings in



All drawings by the author and Russell W. Porter

FIGURE 3

Details of the clock mechanism. The explanation of the action of the mechanism indicated on the margins of this drawing were adapted from a circular issued by the Synchronome Company, Ltd., and it will be well worth while to stop here long enough to gain a full and clear understanding of the cycle thus described, before attempting to understand the chapter. The actual clock face is connected with this mechanism by means of an electric circuit, and the hands of the clock are operated each half minute by means of the mechanism shown in Figure 10. This may be placed wherever desired, or a series of these secondaries may be connected in the circuit with the master clock; in fact, this arrangement is widely used in manufactories in Great Britain. For example, there are 680 dials at the Imperial Chemical Industries, Ltd., all in circuit with one master—not, of course, used for astronomical purposes but for accurate master control of time-keepers. Such a clock should be accurate within one second per week.

the chapter, a reduced scale is given. The rear holes should be provided with cheese-headed or fillester screws and the front ones with studs for wing nuts. Two spacers in the form of thick washers are to be made for placing under the rear end of the clamps, to prevent binding the pendulum support and to allow it to be adjusted when the clock is assembled. The clamps are made of pieces of cold-rolled steel 2½″ by ⅜″ by ⅛″. Holes are drilled in each end for the screws and studs mentioned above, and spaced

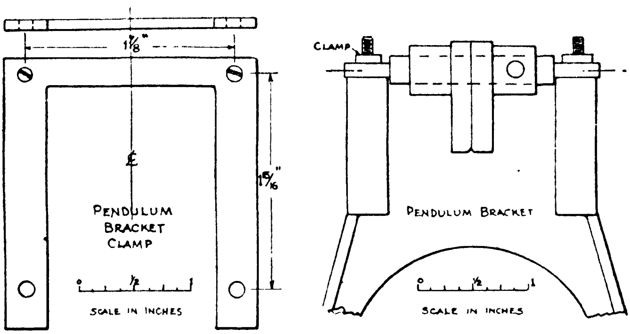


FIGURE 4

The arrangement of these two items on the actual clock does not show clearly in any of the illustrations. Cast integral with the baseplate are two brackets, shaped like triangular wooden shelf brackets, and they extend toward the reader. The clamp shown at the left rests horizontally, with prongs toward the reader, on top of this bracket. The right-hand drawing shows this "clamp" in elevation and under the washers, above which the wing-nuts will be screwed down—the latter show in Figure 1. Special warning is given the reader that each individual drawing in this chapter has its own scale, and that these scales differ considerably.

1¹⁵⁄₁₆″ apart. Use a drill about two sizes larger than the clearance size for the screws.

To finish the brass casting for the upper clamp that holds the suspension spring (Figure 5), chuck it in the lathe by the shorter boss. Face the inner surface and turn the cylindrical part to ⁷⁄₁₆″ in diameter. Then place a ¼″ drill in a drill chuck in the tail-stock of the lathe and bore a hole diametrically through it. To insure a good job a smaller lead hole should first be drilled through the piece, following afterward with the ¼″ drill. The diameter of the smaller drill should be about equal to the width of the point of the larger drill. The second drill will follow the hole whether or not it is straight. The clamping plate, made of a small piece of faced brass ³⁄₁₆″ thick, is drilled and then the hole is enlarged by boring it to a good fit on the larger boss. Drill, tap, and countersink holes in the castings for the clamp screw that holds the suspension spring for the pendulum, and provide a set-screw to hold the clamp in position on the trunion.

A piece of round ¼″ cold-rolled steel will serve for making the trunion.

Cut it to length and turn each end to 1/8″ diameter for a distance of 7/16″. It should be an easy fit between the brackets on the base plate.

The lower spring clamp (same figure) may be made from a brass casting or from a piece of 1/2″ square brass rod. The surface against which the spring bears should be faced in a lathe or planed in a shaper. It must be true. The spring itself is a piece of spring steel 0.005″ thick and 1/2″ wide, the grain being placed vertical. A piece about 7/8″ long will be needed. It is too hard to drill smoothly but it may be punched. The writer placed

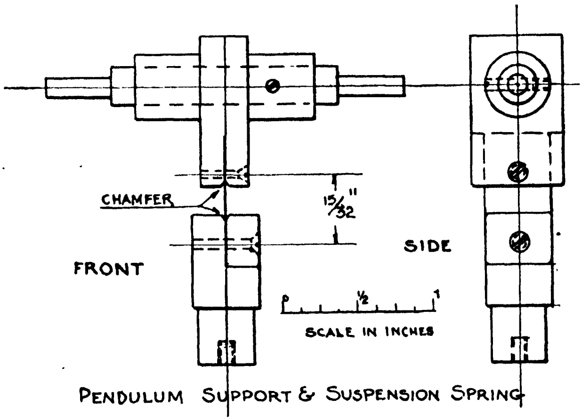


FIGURE 5

a nail-set in a chuck in a drill press, the spring over a hole of proper size in a piece of cast iron, and punched out the metal by a quick movement of the drill press feed lever, the press not being run, of course. These holes should be large enough to provide a slight clearance for the clamping screw. A neater job will result if the screws are countersunk even with the surface of the fitting. A small piece of the spring should be placed between the upper parts of the clamp to insure even pressure on the spring when the screw is tightened. Be certain that the spring is really clamped and is not held merely by the screw acting as a pin. The portions of the two clamps against which the spring will flex as the pendulum swings, should be chamfered slightly, to lessen the danger of the spring breaking. Drill and tap the lower clamp 10-24 A.S.M.E., so that the pendulum rod may be screwed into it later.

The pendulum rod is a piece of alloy steel rod, called Invar, 42″ long. It contains about 36 percent of nickel and has a very small coefficient of expansion. Turn one end of the rod to 0.190″, the major diameter of a 10-24 A.S.M.E. screw, for a distance of 3/8″, and thread it in the lathe with 24 threads to the inch. This can easily be done if a very sharp tool is used at a slow speed and a good cutting oil is generously applied to the thread and

tool. The other end of the rod should be threaded the same size, for a distance of 3¼″, after turning it to the proper diameter, 0.190″. The screw should be finished with a die, after cutting it to about three-fourths depth in the lathe. If this precaution is not taken, the screw will probably twist off because the alloy is very tough and the diameter of the screw too small to have the strength required.

The bob: The pendulum bob (Figure 6, at left) may be placed on an adjustable nut at the lower end of the rod. Made in this way, the clock will have a large temperature coefficient hence it is compensated (Figure 6). The bob itself is a brass-encased cylinder of lead weighing between 10 and 16

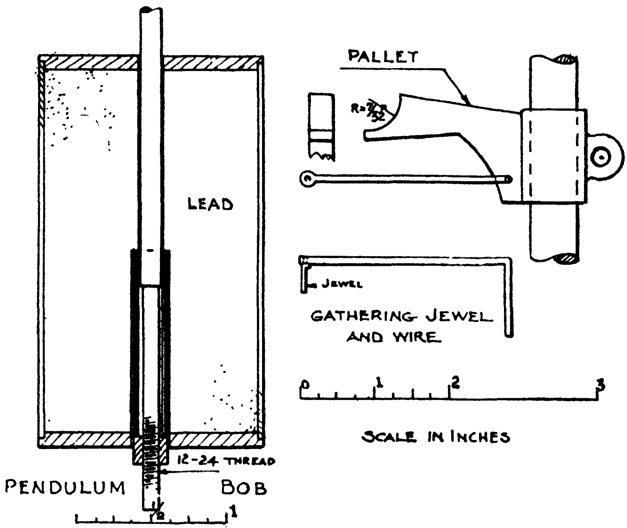


FIGURE 6

pounds. The writer's weighs 13¼ pounds, and is 5¼″ long and 3″ in diameter. Both end plates should be turned with a recess made a light driving fit into the end of the brass tube, which is also faced. The small tubes which make the passage for the rod should telescope a sufficient distance to hold each other in place while the melted lead is poured in. After the lead has cooled, the upper plate may be driven into place. The upper tube should be a sliding fit for the pendulum.

The bob may be made with the point of support at its center, but better compensation should be obtained if the lengths of the two portions, above and below the point of support, are calculated so that a change of temperature will raise the center of mass of one as much as it lowers the center of mass of the other. The larger brass tube forms a recess for the bushing that

rests on the regulating nut at the lower end of the rod. This nut may be screwed up or down on the rod, thus changing the effective length of the pendulum.

An explanation of the manner in which the compensation is effected for a change in temperature may interest some readers. If the temperature of the room rises, the Invar rod expands, thereby increasing the effective length of the pendulum, and the clock should accordingly lose over its previous rate. But the loose brass bushing will also expand, thus raising the lead weight slightly on the rod. If the two changes are made equal, they will cancel each other and the rate of the clock will remain constant, since the position of the lead weight will not change.

The length of the bushing in use is about 2.50″. An attempt was made to calculate the proper length of the bushing, using published data for the coefficients of expansion of the materials of which the pendulum assembly is composed—brass, Invar, and steel. The length indicated was much too long. This was probably due to the lack of measurements for the particular pieces of metal in hand. A change in position of the bob of 0.001″ will cause a difference in the rate of the clock of about one second per day.

The pallet (Figure 6, at the right) is made from a special casting. It is cleaned up, and a hole 5⁄16″ in diameter drilled in it, so that it will slip on the pendulum rod easily. Drill and tap the lug for an 8-32 A.S.M.E. screw. Then split the lug with the jeweler's saw so that the pallet can be clamped on the rod with the screw, at the proper place which will be found later. A small hole is drilled (No. 58 drill) for the gathering jewel support wire, as indicated in the figure. A piece of wire is flattened at one end, and then bent into a loop for the agate jewel,* which is cemented in place with dry shellac. The wire is carefully warmed against a hot soldering iron and a bit of shellac placed in the loop. The jewel is then inserted and squared while the shellac is still plastic, with its flat side vertical when in position on the pendulum rod. Allow the shellac to cool and the jewel will be found securely fastened. Bend the wire sharply at right angles toward the jewel, at a distance of 1⅜″ from the center of the jewel. About ½″ of the wire should be provided for the bearing. Insert the wire in the hole in the pallet and bend again sharply at right angles, in such a way that it may rest against the round portion of the casting. It must be adjusted until there is no binding whatever in its bearing. The exact position of the jewel is important and this must be adjusted vertically within a few thousandths of an inch of the roller, when resting in the bearing under its own weight.

The Gravity Arm: The gravity arm is filed to shape, making it the size given in Figure 7. It should then be drilled for the ⅛″ pivot, either on a lathe face-plate or in a drill press. In the latter case the gravity arm should be held securely in a drill press vice to ensure a true hole. It is best to use

* This was purchased from a manufacturing jeweler and is the type used in the escapement of many clocks. It is about 1⁄16″ in diameter, ¼″ long, a cylinder, and about half of its diameter is ground away for about half its length.

a C-clamp to hold the vice on the drill press table, lest the drill catch in the metal as it goes through the casting.

The roller is carried between the arm itself and a small bearing plate of brass supported on the end of the bracket of the gravity arm. This plate should be fastened with two countersunk screws, size 2-56. The bearing hole may be drilled in the front bearing plate, which is then fastened in place, so that the hole for the rear bearing may be located in exact alinement. For this purpose, the whole arm may be clamped in the drill press vice so that

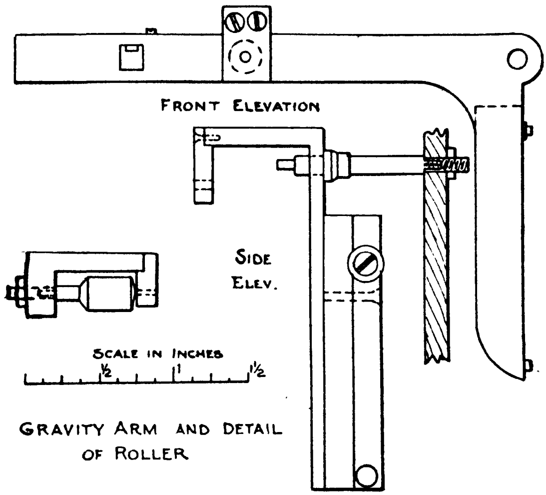


FIGURE 7

the drill will pass through the hole when the feed handle of the press is moved up and down. Care must be taken to see that the drill is accurately centered and does not rub against the surface of the hole. If it does so, the vice may be tapped lightly with a wooden mallet, in the proper direction, if the C-clamp is eased a bit. It should be emphasized that great care is required to make all bearing holes in the correct positions, for an error of a couple of thousandths of an inch will cause so much friction that the bearings cannot be made to turn. When the correct position is found for the vice, tighten the clamp, exchange the small drill for a stiffer one, after the top plate is removed, and mark the position of the hole in the arm by touching the metal with the drill while the press is running. The slight depression in the brass will be in the right spot, and the hole can be drilled through the bearing. Tap it 6-32 to take the rear bearing, which consists of a 6-32 screw with a $\frac{1}{16}$" hole drilled in its center. A simple way to do this is to drill and tap a hole that size in the end of a steel or brass rod held in the chuck. Turn

the end of the rod to about ½″ in diameter for a short distance, to make the hole truly centered. Then cut off about ⅜″ of the rod, and a jig is at hand for holding screws for drilling or for cutting to length. The screw to be drilled is locked in place with a nut at the back end of the jig, the latter held in a universal chuck or centered in a four-jaw chuck with an indicator.

Make a 5⁄32″ square hole in the arm for the arm-retaining spring and fasten the spring in place with a screw and a steady pin so that it does not move. A piece of Bakelite or hard rubber is then fixed to the side of the vertical limb of the gravity arm, with two 4-32 countersunk screws, screwed into the arm. If Bakelite is used, threads may be cut in it with ordinary taps and a piece of brass the same size screwed into it with countersunk screws, the holes in the brass being "pass size" and the tapped holes being in the Bakelite. The screws must not reach through and touch the arm itself, for the purpose of this construction is to insulate the brass strip. A hole is then drilled and tapped near the upper end of the strip, for a screw and washer that will serve as a binding post for one of the electric wires. At the lower end of the same strip, drill a hole and rivet into it a platinum or silver contact point. The latter metal is the cheaper and, since its oxide is a conductor of electricity, it serves satisfactorily. Its diameter should be about ⅛″.

The steel roller is turned from a piece of ¼″ round cold-rolled steel rod, to the dimensions shown in Figure 7. The surface of the roller should be highly polished with crocus cloth and oil to minimize friction.

The Count Wheel Assembly: The mounting of the count wheel assembly is probably the most difficult step in the whole construction, because two pairs of bearing holes must be located with extreme accuracy. First, drill and tap a hole in the center of the tallest boss, for an 8-32 screw. Then drill a hole for the screw, pass size, in the V-shaped bearing plate. Now locate the bearing holes with a pair of dividers, 2 3⁄16″ apart on the plate, and drill them to size. Fasten the bearing plate in position and place the back-plate on the drill press table, with one bearing hole exactly under the center of the spindle. This can be determined by placing the drill in the chuck and lowering the spindle with the feed arm, as explained previously. It is also necessary to see that the back-plate is clamped level on the table, so that the bearing plate will be drilled squarely with it. This can be insured by testing the position of the back-plate by means of a level and then checking it by placing the level on the bearing plate. If a sensitive machinist's level is used for this test the bearing will be parallel with the base-plate. If the boss has been machined with a planer or shaper, the test for parallelism is unnecessary, of course, but the plate must nevertheless be level. With the plate securely clamped in position and a rather stiff drill in the chuck, the position of the hole for the bearing in the base-plate can be found. Then drill and tap it for an adjustable bearing made from a 6-32 screw. The other bearing, which will hold the pivot for the gravity arm catch, should be located, drilled and tapped by a similar procedure.

The count wheel and its bearing should next be assembled. Turn the

spindle to the size given in Figure 8, at the lower right, and cut it to length. Then turn up two small brass bushings, according to the dimensions given in the figure. One of these is to be provided with a shoulder against which the 15-toothed wheel should be soldered. Adjust the position of the bush with the wheel soldered to it, on the pivot, before the bush is soldered to the pivot. Be careful not to use an excess of solder as it might destroy the balance of the wheel, and be sure to get the wheel square with its axis. This can best be determined by revolving it in its own bearings. It should show no wobble when spun rapidly. The second bush is soldered back of the first

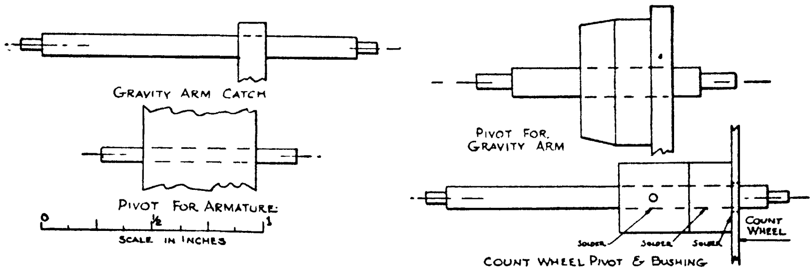


FIGURE 8

and a hole is drilled in it, diametrically, for inserting a small wire about $\frac{1}{32}''$ in diameter that will trip the gravity arm catch once each revolution of the wheel.

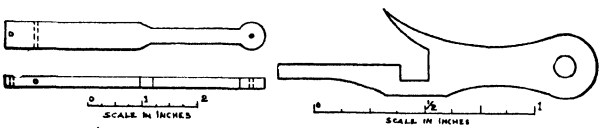
In order to prevent the count wheel from back-spinning, some device must be provided to act as a positive stop. This can be easily done by screwing a little square post into the under side of the boss. Drill a hole through one side of the post to take a piece of wire. A piece of capillary tubing provides a satisfactory roller which may be mounted as shown in Figure 3, on the wire which moves freely in its bearing.

The gravity arm catch (Figure 8, at the upper left) is filed to shape from a piece of $\frac{1}{8}''$ sheet brass. Drill a hole to take a $\frac{3}{32}''$ pivot and solder the catch in place. A hole should be placed in the brass near the pivot, for one end of the small spiral spring which keeps the catch in contact with the gravity arm. The hole for the other end of the spring can be drilled only after its position has been found for the particular spring in use. Provide only very slight tension in the spring, because too much will cause the pendulum to vibrate rapidly when receiving its impulse.

The Electromagnet: Drill two holes $\frac{1}{4}''$ in diameter in the projection at the bottom of the base-plate for holding the electromagnets, their centers being $\frac{7}{8}''$ apart. The two soft iron cores are already provided with clamping screws. Turn four disks $\frac{3}{4}''$ in diameter and $\frac{1}{16}''$ thick. Bore a hole in the center of each, so that it can be tightly pressed on the end of one of the cores. If each is fitted individually, a satisfactory bobbin will be formed.

Drill a hole at the right-hand end of each bobbin, just large enough to take a single strand of the wire and as close to the core as possible. Wind on the core a layer of waxed paper or other thin insulating material, followed by 800 turns of 25-gage s.c.c. wire, putting ten layers of 80 turns each, on each core. Wind the wire first around the lower bobbin, leaving about 6" of it for fastening to the armature. The second bobbin should be wound in the same direction as the first, so that its field will reinforce that of the other. The short length of wire between the bobbins should be soldered together. One end of the wire is connected to the lower terminal and the other to a screw provided with washer and nut, at the lower end of the armature.

The armature, (Figure 9, at left) may be made from a piece of ½" by ⅛" soft iron 4¾" long, filed to the shape shown in the figure. At the point 9/16"



ARMATURE CATCH FOR GRAVITY ARM

FIGURE 9

from the lower end, drill a 1/16" hole through it edgewise for its pivot. Also drill the hole for the tension spring. About half way between this and the hole for the pivot, drill, tap, and countersink a hole for a 2-56 screw. By means of a nut, one end of the wire from the lower bobbin should be fastened to the armature. The other end of the wire is held in the end of a screw in the magnet support, the screw being locked in place by a nut, after the proper tension has been found for it.

The brass bearing plate for the armature bearing, shown in Figure 3, should be filed to shape and drilled with a countersunk hole for the fastening screw. Drill and tap a hole in the boss at the lower right hand corner for the bearing plate that supports the armature. Drill the bearing holes 1/16" in diameter and fit the one in the base plate with an adjustable bearing as previously described.

The two binding posts and the stops that control the movement of the armature are to be installed at this time. Both binding posts should be insulated from the back-plate with washers. Wrap a little piece of varnished paper or other insulating material around the screw that passes through the back-plate, or drill out the hole so that there will be ample clearance around the screw.

Assembly: In assembling the clock it must be remembered that there are two very easily damaged parts of the mechanism, the clock spring and the agate jewel.

Mount the count wheel and the gravity arm. See that there is the least detectable end play in each bearing, oil with a trace of sewing machine oil or light non-gumming oil, and then tighten the nuts that adjust the back bearings. The wheel should spin easily if mounted properly. Then adjust the

gravity arm. Turn the count wheel slowly by hand, to be sure that the release arm wire is the proper length. When it has been found that the wire will not catch, it is safe to try releasing the weight by the pendulum, but move the pendulum slowly by hand for the first trial. If this trial were made by allowing the pendulum to swing of its own weight, the jewel would be broken if all were not just right. The shorter end of the wire should not touch the catch when the wheel is revolved. The spring should be just strong enough to keep the catch in contact with the gravity arm. Adjust the tension on the armature spring, so that the resetting of the weight can be accomplished without jarring the pendulum.

When these adjustments have been made, the electric circuit should be connected up. The magnets are placed in series with the source of direct current, contact being made through the silver or platinum contact points.

There are four adjustable factors that can be used to prevent vibration of the pendulum.

1. The position of the pendulum trunion between the two brackets.
2. The tension of the spring on the catch that holds up the gravity arm. This is very important.
3. The position of the armature at rest and at the end of a power stroke.
4. The tension of the spring that holds the armature away from the gravity arm.

When the pendulum is at rest the agate jewel should lie about half way between two teeth of the wheel. See that the pendulum swings enough but not too far, for in that case two teeth may be gathered instead of one. By moving the whole pendulum right or left a few thousandths of an inch, the amplitude of the swing will change perceptibly, and vibration of the pendulum will be increased or lessened, according to conditions.

The tension of the spring on the catch is important for two reasons: it seems to influence the vibration of the pendulum, and largely controls the noise made by the resetting of the gravity arm. Some experimenters have faced the catch with leather, to reduce the amount of noise.

A change of an eighth of a turn of one of the stop screws often will change the vibration of the pendulum. Only by experiment can the correct position be found. Under this circumstance, no vibration of the pendulum can be detected by sight or by a light touch as the impulse is given to the pendulum. As a guide for finding the best condition, it may be stated that the armature and the gravity arm should travel together during three-fourths of the total travel, and that a gap of about ¼" will be found suitable for the first trial.

The tension of the spring that holds the contact points apart should be sufficient, but too much will drain the battery.

Power: A direct current is required to operate the clock. The best source of power is two or three common dry cells. They are reliable and the drain on them is very little. A storage battery could be used, but the current drawn from it would not be sufficient to keep it in good condition. The clock requires only 5 watt-hours per year.

Mounting: The clock should be mounted in a dust-proof case, fastened by screws to a vertical wall and the case should not touch the floor, because the latter transmits all the vibrations of traffic and the jar of persons walking in the room. A level should be used to insure the clock being plumb in both directions. A masonry wall in the basement is a satisfactory support of the case, if the basement is dry enough so that the steel parts of the clock do not rust.

Regulation: The clock can be regulated fairly closely with a good watch, but the only way the writer knows to rate it with the accuracy with which it is capable of running is to compare it with the Government time signals sent out by wireless by Station NAA. The signals are given 20 times a day, none being given at 9 and 11 o'clock, morning and evening. The most suitable wavelength is 113 KC. Amateurs with short-wave receivers can get signals with these. For those who live within a few hundred miles of Arlington, a broadcast receiver can be used for the signals at noon and at 10 P.M., Eastern Standard Time. The wavelength is 690 KC. Often a Canadian station of the same wavelength interrupts the signals.

If the clock is to be adjusted more accurately than a second a day, the final adjustment should be made by adding small brass weights to the top of the pendulum bob, previously having given the clock a slight losing rate. The accuracy with which the clock can be made to run depends on the constancy of the temperature and pressure in the room in which it is located. A change in the barometic pressure of an inch corresponds to a change of 0.3 to 0.4 second per day in the rate of the clock.

The free pendulum clocks in observatories are often kept in constant temperature rooms, the clock itself being in an air-tight case from which most of the air has been exhausted. It has been found that the circular error of the Synchronome pendulum is balanced if the pressure in the case is kept at about 0.78" of mercury.

The Dial Movement or the Secondary: The mechanism so far described will send an electrical impulse through the wires at intervals of one half minute. Another device is needed to record them and to indicate the time of day.

The secondary movement (Figure 10) contains three gear wheels; upon the shafts of two of them, pinions are mounted, while the shaft of the third is hollow. An electromagnet is placed in series with the magnet of the master clock. It is arranged so that, when the magnet is energized, a small lever is released which is at once actuated by a spring, thus moving the wheel one tooth. The wheel has 120 teeth, so the movement of one tooth corresponds to ½ minute. The following statement of the requirements of the train of wheels may assist some of those who make the clock. The large propulsion wheel has 120 teeth. It is mounted on an arbor with a ten-tooth pinion. This pinion meshes with a wheel having 30 teeth, which in turn is mounted on an arbor with an eight-tooth pinion. The pinion meshes with a third wheel having 32 teeth mounted on a hollow arbor to which the hour hand is at-

tached. The motion of the minute hand is slowed down 12 times by the gear train, as may be seen from the following equation: $30/10 \times 32/8 = 12$.

The wheels for the writer's clock were purchased from the Synchronome Co. Ltd., of London. By carefully studying the plate, no difficulty should be experienced in making the secondary. The only trouble the writer had

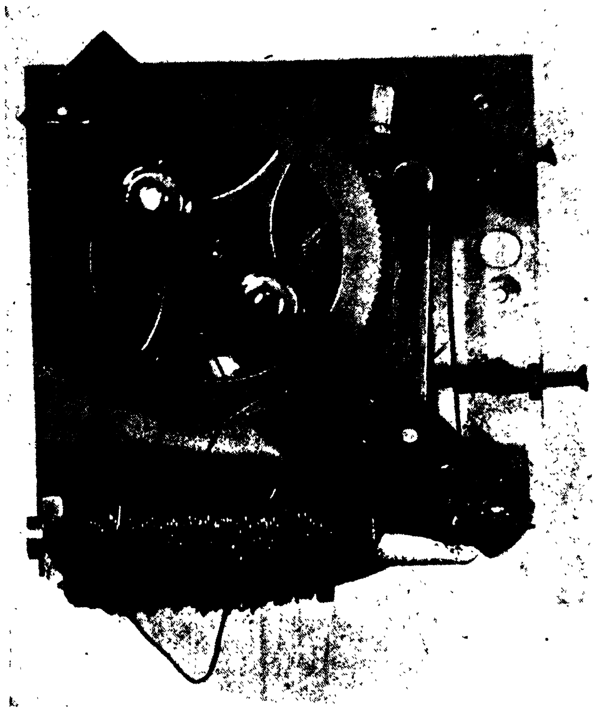


FIGURE 10

The dial movement or secondary. On the reverse side there is an houı and a second hand.

was in finding a suitable spring for propelling the wheel. It was solved by using a piece of phosphor bronze spring 0.010″ thick by 3⁄16″ wide. The free end of the spring was 2 1⁄16″ long.

[EDITOR'S NOTE: Precision in timekeeping is a relative, never an absolute, thing. Probably the earth in its rotation is our most precise clock but present indications are that even it may vary slightly in its rate. There is no perfect man-made clock. The most precise clock made would not continue to

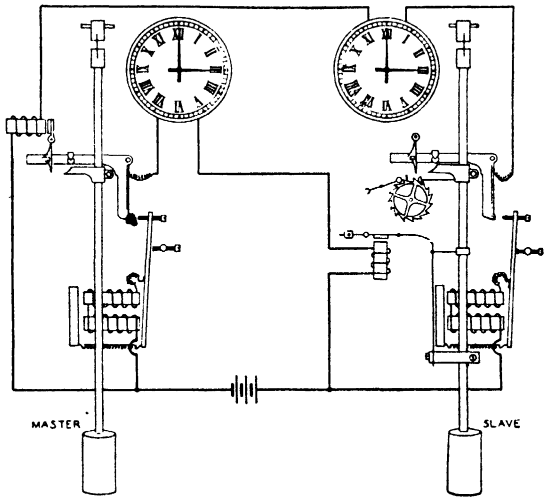
give the correct time: (1) It will gain or lose, (2) its rate of gain or loss will vary. The first factor is of little consequence in itself since if we can ascertain the amount of gain or loss—the "rate"—we can easily calculate how many seconds to subtract or add to the indicated time. But if the rate frequently changes, this is difficult. Hence a good clock is one which has a uniform rate or, next best, one whose rate, when it changes, does so abruptly and then "stays put" for a long time before changing appreciably again.

Just as the fine Seth Thomas clock described in the previous chapter kept still more precise time when especially equipped with a mercury bob, so the clock described in the present chapter ought to keep even better time. The former, like most familiar clocks of low and high degree, is driven by the pallets of an escapement which is constantly interfering with the free swing of the pendulum, but the latter is driven when the pendulum is passing through the middle of its swing, and is free at all other times. In 1827, Airy pointed out that irregularity of impulse at the ends of the swing changes the time-keeping; at the middle it may be made to have little or no effect. In addition, the compensated invar pendulum of the Synchronome clock is superior to the mercury-compensated bob.

A high-grade Riefler clock with its invar pendulum gives a finer performance than the clock described in the preceding text, mainly because its pendulum is almost free from escapement interference.

A crystal oscillator, consisting of a crystal of quartz maintained in vibration by means of vacuum tubes in their proper circuit, has surpassed both of the clocks mentioned for short runs of a week or two at a time, but the construction of these oscillators is not simple, the maintainance is relatively difficult, and the cost relatively high (see *Proceedings National Academy of Sciences,* July, 1930). The true function of the crystal oscillator or mechanical resonator is not the accurate measurement of time over long periods but the division of short periods with extraordinary accuracy. The world's most accurate time keeper is the Synchronome Shortt Free Pendulum Clock (Figure 11). This is precise to something of the order of a second a *year.* Precise as is the pendulum described in the building instructions in present chapter, it does a small amount of work when the count wheel is turned and the gravity arm is released. Mr. Hope-Jones, the founder of the Synchronome Company, Ltd., had announced early in this century that he would never be satisfied until the pendulum was relieved of all such work, and thanks to the genius of his friend, Mr. W. H. Shortt, of Exeter, England, who produced a suitable synchronizer, he was able to use a duplicate synchronizer clock as a "slave." The slave runs the count wheel, taking that work off the master pendulum, and controls the impulse given to the master pendulum. The two are automatically synchronized at all times. The mechanism and circuit are shown in Figure 11, and further described by Loomis and Marrison, in the *Transactions of the American Institute of Electrical Engineers,* June 1932, pages 527–537, as well as the *Journal of the Royal Society of Arts* (by Hope-Jones), May 23, 1924, and in references given at the end of the present note.

The Synchronome Co. has made 60 of these free pendulum clocks for the world's principal observatories. Their workmanship is superfine and their reputation is such that we should not expect them to put it in jeopardy by permitting others to make it. The amateur is likely, however, to feel that even a second a week—the order of precision of the clock described in the present chapter—makes of it, to say the least, "quite a clock!" In fact, an amateur known to have constructed an astronomical clock that will keep time within a second a week is likely to be bothered quite sufficiently by curious neighbors and newspaper reporters. If he should mention clocks that were precise to one second or less per *year* (A Synchronome Free Pendulum at Cape Town Observatory measured time with an accuracy of 0.3 seconds per year and the one in Paris Observatory did the same throughout



Courtesy Trans. A.I.E.E.

FIGURE 11

Schematic drawing of the free pendulum and slave clock. This should not be confused with the simpler clock described by Dr. Souther in the present chapter. The arrangement shown above is the one used in the large observatories, keeping time on something of the order of a second per year, and it has two pendulums instead of one. The patentee's permission to construct the one described by Dr. Souther does not extend to the one shown above. As there is a widespread belief that anyone may construct a patented article, if for his own use alone, the facts may perhaps be set forth here, in order to avoid possible misunderstanding. No-one may make, even for his own use, a patented article without the authority of the patentee. This is the purely legal aspect of the matter. The broader side is that, in this instance, the patentee, himself friendly toward amateurs, has kindly granted permission to the amateur to make the Synchronome Master Clock (the one-pendulum clock), provided it is not made for sale or sold. The amateur will be grateful for this spirit of friendliness and liberality.

the year 1935) his neighbors and townsmen, instead of thinking him something of a local genius, doubtless would point to their heads and make wheel-like motions. The first Synchronome Free Pendulum was set up at Edinburgh in 1922, and of the 60 since installed in the world's observatories the United States has had its share, including St. Louis University, Lick, Ottawa, Bureau of Standards and three at the U. S. Naval Observatory. One of them ran nearly nine years at Greenwich until it was deliberately stopped—the gravity arm (see Figure 3) falling and being replaced by the armature and magnet 284,000,000 times without a single failure. Mr. Hope-Jones published a monograph to celebrate this occasion. It was addressed to laymen and not to scientists, but presents such a faithful picture of an observatory's time determination that it is quoted as follows.

"Let us visit Greenwich in imagination and look at this distinguished aristocrat of the Clock family. The devout disciples of the Prophet take off their boots before entering the Mosque. It is with similar feelings of reverential awe that we shall be permitted, if we are fortunate, to enter the *sancta sanctissima* where the time of the world is measured. It is to be found in a remote cellar which tradition associated with the deepest dungeon of the castle of Humphrey, Duke of Gloucester, on the site of which Greenwich Observatory was built.

"On descending, one arrives first at the outer chamber destined to receive the two Mean Time free pendulums. The temperature of this chamber is controlled by electrical heaters and an automatic thermostat, so one must be careful not to disturb it when entering, but it is not so rigorously controlled as the Sidereal chamber beyond.

"The door of the outer room having been closed, we are at last on the threshold of the inner, and are privileged to gaze upon the two sidereal clocks, the first free pendulums to be installed at Greenwich, mounted at right angles to one another. It is the later of the two which arouses our greatest interest at the moment, since it is the one which has not been touched since its installation in February, 1926. There it is, on the right, bolted to a wall which is 4′ thick and as solid as the rock on which it is built. Its once lustrous case of burnished copper is tarnished, and it is cobwebbed like a bottle of rare old crusted port, but it is still going with an accuracy which has only been equalled or excelled by its stable companions.

"And now it has been stopped—forcibly—since it refused to stop of its own accord. This act of vandalism occurred on the 18th January, 1935. There was no ceremony, but that there was a wish to do honor to the occasion was obvious from the company assembled in the Sidereal chamber, which included the Astronomer Royal, his Chief Assistant for Time, Mr. W. Bowyer, Mr. F. Hope-Jones and Mr. W. H. Shortt. The Synchronome Company's chief mechanic, Mr. H. E. Jones, let the air into the case, removed the glass bell jar and dismantled the movement, the vital parts of which were eagerly examined by the company for signs of wear.

"Its undisturbed run for nearly nine years may be considered as the apotheosis of that simple little device known, for want of a better name, as

the Synchronome Switch. A gravity lever falling with the pendulum and replaced by a magnet 284 million times without a single failure must surely constitute a record.

"To realize the extent to which these clocks have contributed to the science of time measurement, it is necessary to remember that up to ten years ago, when the Graham dead-beat escapement was still in use, their daily rates were discussed in units of one-tenth of a second, whereas the performance of the Free Pendulum clocks is discussed in thousandths of a second. When Dr. Jackson was at Greenwich, before he left to take up his astronomical duties at Cape Town, he said they were measuring time with an accuracy of one part in a hundred millions, *i.e.*, 0.3 of a second per year, whereas previously time measurement was of the order of one part in one million. On this is based the bold statement, now accepted by the British astronomers and scientists of the horological press generally in England, that the performance of the free pendulum is 100 times that of the best escapement which preceded it."

But why does the amateur astronomer need any special kind of clock? Why make one? This is much the same kind of question that the rank outsider often asks the telescope maker when he discovers him apparently making telescopes which he often does not half use. The clock enthusiast is said to be an even worse afflicted specimen of the *genus homo* than the "telescope nut" (difficult to believe). Largely, he gets his fun from making his clock perform. This becomes a fascination if not an obsession. A fine run of a month, with only a slight variation, gladdens his heart and wreathes him in smiles—though he is never satisfied and, exactly like the T. N. who always wants a bigger, better mirror, he always strains and strives to get a closer run. But anything you think is fun, *is*. Nobody can go behind that axiom.

The cost? Dr. Souther, author of the preceding instructions, says that the cost of materials for his Synchronome Clock—the one he describes—was about $20. He states that the record for his clock is 0.17 seconds a day for a week.

Other data: The battery that lifts the gravity arm "will die of old age," as stated by the Synchronome Company. That is, the actual current consumed is so slight that its work runs it down less than the time factor. As it finally becomes senile, much like any unused battery standing on a shelf, the duration of contact is increased, but it will still plod on for days while thus giving warning; or a lamp may be included in its circuit, "with the charming yet paradoxical result that the weaker the battery the brighter the lamp will glow."

In the United States, time, as taken from synchronized electric power lines, is usually controlled manually from minute to minute against a high-grade pendulum clock such as the Seth Thomas clock. This, in turn, is checked regularly against Arlington wireless signals. These, in turn, are controlled by Shortt Synchronome clocks carefully checked by astronomical observations. In England the generating stations are provided with the ordinary Synchronome master clocks of the kind described by Dr. Souther,

and these are checked daily against the wireless time signals transmitted by the British Broadcasting Corporation in the form of the "six dot seconds" originated by Mr. Hope-Jones.

There is a large literature on horology. Dr. Souther suggests "Horology," by Eric Haswell (London, 1928); "Electric Clocks and Chimes," published by Percival Marshall and Co., Ltd., London, and many articles and letters in *The Model Engineer,* a periodical published by the same house; also "Electric Clocks," by Hope-Jones. Mr. Hope-Jones adds: "I suggest that the bibliography should begin with F. J. Britten, 'The Watch and Clock Makers' Handbook, Dictionary and Guide,' also 'Old Clocks and Watches and Their Makers,' both published by E. and F. N. Spon, Ltd., 57 Haymarket, London, S. W. 1. Mr. Britten lived most of his long life as Secretary to the British Horological Institute. Then you might mention next Lord Grimthorpe's 'Clocks, Watches and Bells.' "

Other literature: *Journal of the Royal Society of Arts,* May 23, 1924, a clear, 12-page exposition by Hope-Jones. (Files available in large public libraries. Published by G. Bell and Sons, Ltd., York House, Portugal St., London, W.C.2). Hope-Jones in the *Journal of the British Horological Institute,* 1895, pages 33–39; 1906, pages 66–67; 1923, pages 174–177 and 197–302. Hope-Jones in *Horology,* Jan.–Feb.–Mar., 1936. A 30-page article on "Clocks and Time-Keeping," in Vol. III of Glazebrook's "Dictionary of Applied Physics" is helpful.

Horological journals:

The Horological Journal. Official organ of the British Horological Institute. Monthly, 5 shillings per year, post free to all countries. 55 Banner St., London, E.C. 1.

Horology. Monthly. $2.00 per year ($2.50, foreign). 747 S. Hill Ave., Los Angeles, California.

Judging by the enthusiasm shown by its followers, horology must be a satisfying hobby. Just as we telescope makers sometimes call ourselves "telescope nuts," so the term "clock maniacs" has been used unconventionally among horologists. Which group can reach the higher level of frenzy it would be rash to say—a competition might be staged, reminding one of a cartoon which showed two hypnotists trying to ascertain which would hypnotize the other. Perhaps the makers of clocks and telescopes are on a par—ask the wife of the man who owns either one.]

Micrometers—a Composite Chapter

An Amateur Micrometer for Double Stars

By Lieut. Eugenio C. Silva

Translated from L'Astronomie, Bulletin de la Société Astronomique de France, by R. O. Sinclaire*

[Editor's Note: The micrometer to be described in this section is of the double-image or split-image type, which works on the following principle. Suppose a lens were to be cut in two and then, after the halves were placed in contact again, they were to be slid edgewise, one on the other, as shown in Figure 1, at the left. They would then give a double image of a single star, each half of the lens giving its own separate image, or a quadruple image of a double star, as shown at the upper, left-hand corner of Figure 2 (where one component is shown larger than the other)—and the more they were moved as described, the wider these images would be separated. In measuring the angular separation of the components of a double, the half lenses are slid, by means of a screw, until the one star component in the image on one of the halves is superposed on the other component in the image on the other half, as shown in "Position 1" in the same figure. (The remainder of the figure may be ignored for the present.) If the screw has been calibrated in advance, this gives the angular separation of the components of the double.]

For about a year I have been using a micrometer which I made more or less along the lines of that described by M. Roth in the magazine for January 1923, but which permits, in addition, the measurement of the angle of position.

Its great ease of construction, its small cost (it cost me 80 cents) and its remarkable precision have impelled me to describe it here.

Construction: The essential part of the micrometer is a bi-concave lens cut through the middle, one half remaining fixed while the other half can slide upon it. I use a simple spectacle lens of 0.50 meters focal length [*Translator's Note:* 2 dioptries. It is hardly necessary to add that the two spectacle lenses from which the split lens is made, as described later, must match precisely as to focus].

The stationary part *f* is mounted on a brass support *L*, and is held in place by a brass half-collar *C*, Figure 1, left; the moveable part *m* is carried in the same way by the slide *G*, dovetailed into a slot in the support *L*. This slide is moved in its own plane by an endless screw *V*, having one bearing in a collar *Co* attached to support *L*, and the other bearing in its pointed end in another screw *v*, which can be adjusted to take up all play. The movements of the slide are read on the scale *E*, graduated in millimeters, and by the drum *T* mounted in the head of the screw, giving $1/100$ of a millimeter.

To make the two half lenses needed, it is necessary to cut into two unequal parts two exactly similar lenses, since this cutting cannot be done smoothly

* February, 1935.

and it is necessary to smooth the edges by polishing, with an appreciable loss of material. The larger portion of each lens is chosen, and each reduced by fine emery until they *exactly* fit together to make a complete lens. It is absolutely necessary to watch the progress of this operation by trying the system of half lenses *on the sky,* using the greatest possible magnification and choosing nights of perfect visibility. The desired result will have been attained when, on the line of contact of the two halves, the stellar disks appear perfectly sharp and absolutely round, a necessary condition for good measurements, especially with regard to the angle of position.

The system of lenses can be examined with a positive ocular (Figure 1,

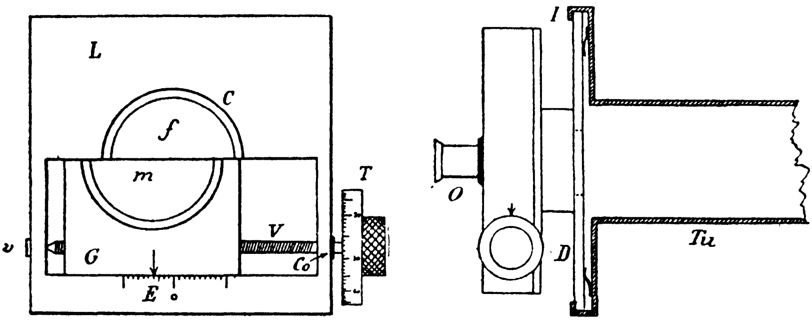


FIGURE 1
Left: Front of the micrometer. Right: Profile of the same micrometer.

right), but this is not necessary, the division of the lens showing up very well with negative oculars, as a fine black line bisecting the image of the star. It is necessary to employ the strongest magnification compatible with a good sharpness of the images. On my equatorial of 110 mm. aperture, I almost always use 220 ×, and sometimes, when the definition is perfect, 330 ×.

Before making any measurements, it is evidently necessary to calibrate the screw. The most practical method consists in measuring a large number of times the separations of double stars whose distances apart are accurately known, with fixed mount. Dr. P. Baize has given a list of them in the *Bulletin* for October 1929. In this way, I obtained $2''.710$ for the value of one turn of the screw of my micrometer, using a series of observations of ν Draconis, ζ Lyrae, and β Cygni.

To measure the angle of position, the optical part of the micrometer is supported by a disk *D* (Figure 1, right) of very hard wood, graduated in degrees and half-degrees, tenth degrees being easily estimated. This disk, turned by hand around the optical axis of the telescope, runs in the ocular tube *Tu* of the telescope. Readings are made with the index *I*. The division of the lens, visible as a very fine line, replaces the spider line of the ordinary micrometer.

Method of Use: Begin each measure by determining the angle of position. Put the image of the star a little outside of focus, showing sharply the lens division line, and orient the micrometer until the star, traversing the field from east to west, exactly follows this division, remaining bisected by it. Turn the micrometer through 180° and repeat the reading, the average of the two settings giving the diurnal direction of movement E—W.

Put the star carefully in focus once more, and turn the screw through several divisions. In the field, one sees two images of the double star, sepa-

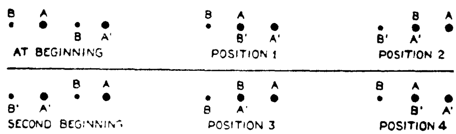


FIGURE 2

rated from each other. Then turn the micrometer until the four images are seen on one straight line, then read the dial setting. Turn the device through 180° and repeat the reading. Then interchange the position of the two pairs of images, and repeat the above process. We thus have secured four readings of all the possible combinations of the two images, eliminating systematic errors. The difference between the average M of these readings and the value obtained previously for the diurnal movement gives the position angle P, which one refers to the meridian by adding $\pm 90°$ if the companion is at the east, $\pm 270°$ if at the west of the principal star.

For the separation, the four stars $A'B'AB$ being on the same straight line, displace the moveable lens by turning the screw so as to obtain perfect coincidence of the star B' with star A, reading the slider scale (Position 1, Figure 2). Continuing to turn in the same direction, bring the star A' into perfect coincidence with B (Position 2), with a new reading. Then move the slider so as to move $A'B'$ beyond AB on the opposite side from before. Then, by turning the screw in the opposite direction, repeat the preceding operations (Positions 3 and 4), each time reading the position of the slider. It is easy to see that Position 4 reproduces Position 1, and that Position 2 is identical with Position 3. This procedure (comparable with the method of double distances with filar micrometers) reduces to a minimum the errors due to errors in the screw.

The average of the reading made in 1–4 and in 2–3 being made, their difference represents double the angular distance of the pair AB. A simple multiplication by the value of one turn of the screw and division by 2 immediately gives the true separation in seconds of arc.

Results: Experience has shown that with this device, one can measure pairs where the distance is not less than 2″; below 2″, if the distance can always be obtained as easily as for more separated pairs, the position angle becomes rather doubtful.

The magnitude of the components must not be less than 8 on the Harvard

scale, because of the necessity for each star to give two images, entailing a loss of light which is appreciable. This disadvantage, however, is no worse than that resulting from the lighting of the field in ordinary micrometers.

The field accessible to a micrometer of this type, adapted to telescopes with apertures of 100–150 mm., such as are ordinarily used by freelance as-

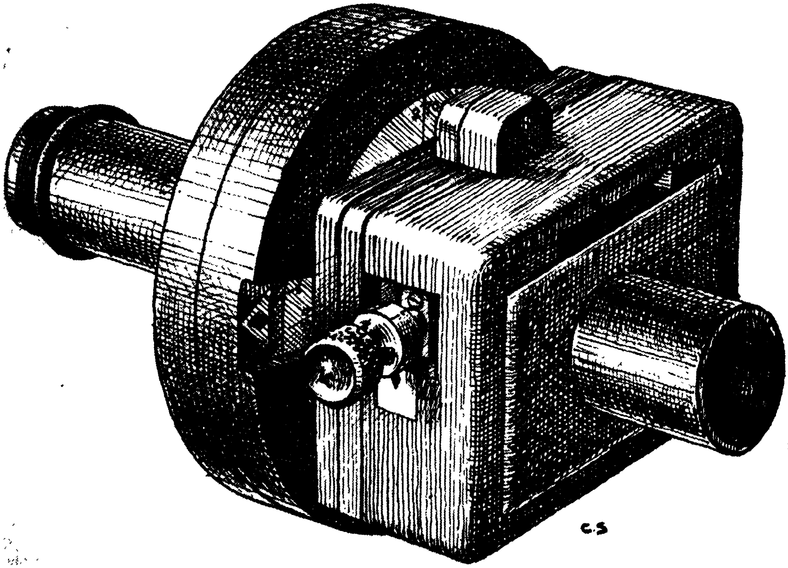


FIGURE 3

The finished micrometer. Drawn by the author, especially for "Amateur Telescope Making—Advanced."

tronomers, is thus strongly limited. Nevertheless, there is a large number of interesting doubles that are measurable under these conditions, and the results quoted below will show, I hope, that one can do useful work with these modest means.

First, here are the details of measurements of a few doubles observed on my 110 mm. equatorial. Their agreement from night to night is obviously satisfying: *

* The first column contains years and hundredths of years. The second column, which is the position angle, is in degrees and tenths. The third column is the angular separation in seconds and hundredths. The *n* refers to the number of nights the star was observed. This does not necessarily mean the number of observations, for a man might make a dozen obs. on one star in an evening.—Explanation kindly furnished by Margaret Walton Mayall, Harvard College Observatory.—*Ed.*

γ Delphini

1934.55	270°.3	10″.15
56	271.2	10.31
71	269.7	10.37
71	270.7	10.45
72	270.2	10.30
1934.65	270°.4	10″.32 5*n*

γ Virginis

1934.40	317°.8	5″.65
34.43	318.9	5.65
34.44	317.5	5.73
1934.44	317°.6	5″.88
34.45	317.9	5.91
1934.43	317°.9	5″.76 5*n*

ζ Aquarii

1934.55	292°.7	2″.66
56	292.2	2.78
58	293.3	2.51
80	294.4	2.52
81	290.0	2.59
1934.66	292°.5	2″.61 5*n*

The following table permits comparison of the measurements obtained with the micrometer just described and the measurements made recently by astronomers provided with more perfect tools.

70 Ophiuchi

1933.60	120°.4	6″.77	Phillips	3*n*
33.63	120.2	6.51	Baize	5
33.71	121.0	6.57	L. J.	3
34.54	118.3	6.74	Silva	5
34.64	119.5	6.57	Baize	3

γ Delphini

1931.72	269°.9	10″.36	Hargreaves	3
33.80	269.6	10.25	Aller	2
34.65	270.4	10.32	Silva	5
34.82	269.1	10.41	Baize	2

ζ Aquarii

1932.69	295°.5	2″.94	Komendff	3
1933.86	293°.2	2.54	Baize	4*n*
1934.66	292.5	2.61	Silva	5
1934.83	291.6	2.37	Baize	4

γ Coronæ Borealis

1928.08	304°.3	6″.53	Fatou	2*n*
29.53	302.8	5.98	Aller	3
30.44	304.3	6.33	Doberck	3
34.44	303.4	6.28	Silva	5

γ Virginis

1932.33	320°.8	6.30	Komendff	4
32.36	319.1	5.79	Baize	5
32.37	318.6	5.57	Aller	5
33.41	318.9	5.42	Baize	5
34.43	317.9	5.76	Silva	5

Gamma Delphini

1934.55	270°.3	10″.15
56	271.2	10.31
71	269.7	10.37
71	270.7	10.45
72	270.2	10.30
1934.65	270.4	10″.32 5*n*

It is needless to multiply these examples, sufficient to show that the apparatus and method is able to attain a good degree of precision.

Before ending, I desire to thank Dr. P. Baize, who, by his advice and by the measurements that he made available to me, has enabled me to write this article.—*Bairro dos Oficiais, Alfiete, Portugal.*

[EDITOR'S NOTE: It is true that the double image type of micrometer just described, from the point of view of the professional astronomer, is mainly

of historical interest, as stated by Bell (171), and by Russell, Dugan and Stewart, it having been invented in 1748 to measure the apparent diameter of the sun—hence its alias, "heliometer type." It has been displaced by the filar micrometer for professional work. However, this fact need not cramp the style of the amateur, particularly if he derives fun from making and using it. Today we have clocks, but still it is fun to make and enjoy the use of sun dials; electric lamps, but it is sometimes pleasant to retire at night by the light of a candle; high powered rifles to bring down big game, but Art Young and Dr. Saxton Pope had no end of fun doing the same thing with a bow and arrow; and steel axes, but the anthropologist Sehested, of Denmark, had lots of fun cutting down trees with a flint axe and building a house, with this and other flint artifacts, and incidentally he found these were a lot more efficient tools than anybody in our day had been ready to suppose. The old-fashioned double image micrometer has this advantage over the more modern filar micrometer: it may be used without a clock drive (so may the filar, but only with extreme difficulty).

Nor is there a way in which the amateur who is equipped with a micrometer may cooperate with the professional, as a motivation for making one. A comment written by Margaret Walton Mayall, of the Harvard College Observatory, in answer to a query on this point, is as follows: "The advanced amateur would probably have lots of fun making the micrometer, but he would not be able to put it to any practical use, for astronomy, since the doubles with a separation as wide as 2″ have been and are being observed thoroughly by the professionals. There are only a very few professional astronomers who are sufficiently experienced to do the work. If those who make a micrometer observe for 10 or more years, they will be able to see the motion of some binaries. For example, the period of *Xi Ursa Majoris* is 59.8 years; there are a few with shorter periods, but only a couple with a period of less than 10 years."

And this from Daniel E. McGuire, Shadyside, Ohio: "Professor Henry Norris Russell's Scientific American article on double stars is what aroused my interest in micrometer work. Of course, about all of the double stars in the universe have been checked up to the utmost precision with large telescopes, leaving little for the amateur to do which would be of value to science. But, still I think it would be lots of fun to check up on the quality of our instruments and compare results with the measurements taken with larger instruments. It ought to be especially interesting to check up on the apparent diameters of the planets and, from our own measurements, estimate their distances."

It is not, however, even necessary to justify the construction of a micrometer on any particular scientific or practical basis—it may be made simply for the fun of it.

There are 5400 pairs of doubles in the northern hemisphere, brighter than the 9th mag.—enough to work on. Aitken of Lick is the principal double star observer of our time. His book, "The Binary Stars," is the standard treatise.

The article by Professor Russell, referred to above, throws some light on double star measurement as practiced micrometrically by the professional, and is therefore reproduced below from the *Scientific American* for May, 1935.]

DOUBLE STARS

By PROF. HENRY NORRIS RUSSELL

There are at least four prerequisites for a successful program of astronomical observation: a good telescope, a good climate, a good eye, and good judgment.

At this point many a reader will stop and in spirit will inquire, "But why a good eye? Are not almost all observations made nowadays by photography?"

In many fields of work this is entirely true. The whole study of spectra is made on photographs; so are the greater part, though not all, of accurate measures of the positions of the stars. Measures of the heat of stars and planets, and the most precise determinations of their light, are made with thermo-electric or photo-electric devices of one sort or another. But there are certain important lines of astronomical work in which direct visual observation reigns supreme.

One of the most fruitful of these is the study of double stars. For a century and a half subsequent to the invention of the telescope, astronomers had known that a good many stars were double, but no one seems to have taken the trouble to measure the distance and direction of one of the pair from the other till Herschel tried it in 1780. A few years' observation showed him that, while most pairs remained substantially fixed in relative position, a few exhibited a regular and progressive motion obviously of an orbital nature. Then, in his own words, he felt "like Saul, who went out to seek his father's asses and found a kingdom." The realm of gravitation extended to the stars as well as the solar system.

It was half a century later, however, that Wilhelm Struve began the first systematic search, recording and measuring all pairs which were separable with his 9″ telescope—more than 3000 in number. Later campaigns with larger telescopes have added to the list, though only Aitken, at the Lick Observatory, has discovered as many pairs as Struve. His recent General Catalog, summarizing the work of the past century, contains more than 17,000 double stars. The southern heavens, south of declination −31°, are not included in this. When the surveys which are still in progress are completed, about 5000 additional pairs should be added to the total, bringing the grand total to 23,000.

Practically all these discoveries have been made by looking at the stars directly through telescopes. The primary reasons are that the vast majority of double stars have a very small apparent separation. Great numbers of pairs, including many of the most interesting, are so close that they can be resolved only with large telescopes. Even with ideal optical conditions the

waves of light coming through the circular aperture of a telescope can be concentrated, not into a mathematical point, but into a small "diffraction disk." The size of the disk varies inversely as the diameter of the clear aperture of the telescope, according to the formula $d = \frac{4.''5}{A}$, when d is the diameter in seconds of arc and A the aperture in inches.

With Struve's 9″ telescope all stars therefore appeared as disks 0″.5 in diameter (which is more than 10 times as large as the real angular diameter even of Betelguese). A pair separated by 0″.5 would appear to be in contact, however wide the real interval in miles between them. With a separation of 0″.4, there would be a single elongated image. Pairs much closer could hardly even be detected. The 36-inch Lick refractor gives a "spurious disk" of only 0″.12, and reveals thousands of systems which are utterly beyond the power of the smaller instrument.

With a suitable eyepiece of high power the skilled visual observer can detect and measure equal pairs right up to this theoretical limit. Unsteadiness of the air, of course, may smear out the images, so that he can do nothing.

The photographic plate is at a hopeless disadvantage. Star images on the negative at best are little round bundles of black silver grains, many times larger than the tiny optical images of the stars themselves. There are several reasons: the light spreads out on the plate, so that the images of bright stars are bigger than those of faint ones and, during the minutes of exposure, when the air is as steady as can be hoped for, the star seems to dance about—not much, but enough to blur its image. Even on the best plates taken with great telescopes it is rare to have star images less than 1″ in diameter, some eight times as big as the optical image itself. Moreover, when the seeing is a little unsteady, the visual observer can take advantage of a favorable moment to make his setting, while the plate records only an indiscriminate average of good and bad—which for the present purpose is much like a mixture of good and bad eggs.

For pairs of unequal brightness photographs are at a still greater disadvantage. The fainter star may be utterly drowned in the expanded image of the brighter and, even if they are widely separated, the image will be over-exposed or else the other under-exposed, and no accurate measures can be made.

There is, therefore, not the slightest hope—or fear, according to which standpoint we adopt—that other means of measuring double stars will put the visual observer out of business. He appears to be in no danger of technological unemployment.

Double star observation has been, all through the past century, one of the most altruistic of occupations. One in two or three hundred of the pairs a man discovers may turn out to be a rapid binary, completing a revolution in 20 or 30 years, so that he may live to follow it all the way around and compute its orbit. But the overwhelming majority move so slowly that 50 or 100 years are required to show that they are actually changing their rela-

tive position. The discoverer's satisfaction here must be that someone a century or two after his death may say, "Thank goodness that faithful old fellow made such reliable measures."

Just because past observers have been faithful and enthusiastic, astronomers of the present suffer from an embarrassment of riches. In principle, every double star should be accurately measured at least twice at an interval of 20 years or more, to pick out the rapidly moving pairs, which should be observed regularly, from the great mass which change so slowly that it is quite sufficient to keep tab on them three or four times a century (provided the observations are accurate). In practice, an observer usually goes over his list at a shorter interval, but he finds that the most interesting objects of all have been neglected.

For wide pairs (more than three or four seconds of arc) fairly comparable in brightness, photographic observation is easily possible and more accurate than direct visual measures. But, even so, there is a staggering amount of labor left for the visual observers.

At this point the function of good judgment enters. Why do we observe double stars, anyway—is it more than a harmless hobby? To obtain knowledge, of course; but the mere knowledge that a star is double is of little profit. In the first place it is from double stars, and from them alone, that we can get direct information about stellar masses. Without this we could not even make a start at a physical interpretation of their internal constitution or their nature. To get the mass we must know the star's distance—given by its parallax—and its orbit. Thousands of good measures of parallax have been made in the last 30 years, but there are only 100 pairs or so for which we have even tolerable orbits. This happens because one cannot calculate the orbit of a double star reliably until it has been obscured over the greater part of a revolution. With a century of observation available for the easier pairs, and less than half as much for the more difficult objects, only pairs with periods less than about 200 years in the first case, and 80 or 100 in the second, are yet available.

Now the stars are much more alike in mass than in anything else—which means that a period of 80 or 100 years corresponds to a distance comparable with that of Neptune from the sun. To be resolved telescopically such a pair must be within three or four hundred light years—which is much nearer than the majority of the stars of the eighth and ninth magnitudes. Our list of orbits is therefore a selected list of stars nearer than the average. The few systems with large apparent orbits and easily observable with small telescopes have, without exception, large parallaxes and are among the nearest stars. Suppose, then, that a modern observer starts out to hunt for double stars which are likely to be in rapid motion, and add to our lists of reliable orbits and well determined masses, during the lifetime of the younger at least of present-day workers. What should he do? The obvious answer is to observe the *nearer* stars. Among these he can detect pairs of small real separation and of correspondingly short period.

[Editor's Note: In addition to the double image type of micrometer

previously described, and the filar type to be described in the next section, there is the ring type. This is mentioned in Bell, and its theory and use are explained in "The Splendour of the Heavens." Still another type is the cross-bar micrometer whose use, but not construction, is described in the last-named book. These types are used largely for measuring the angle between some known star and a comet, asteroid or new star. All of these have no screw, like the filar type, and so they require the use of a simple timepiece.

T. E. R. Phillips mentions the fact that all micrometers work best on refractors, and suggests the addition of a Barlow lens when they are to be used on reflectors.

The filar type is the most modern instrument and is commonly used for measuring doubles, for measuring the diameter of the planets and of planetary and lunar detail—for example the snow caps of Mars, or for working out trigonometrically in miles or feet the width of some tiny lunar detail. It is not suitable for work on objects having wide separation.]

A Filar Micrometer

By Russell W. Porter

This instrument is an attachment at the prime focus of a telescope, to measure small angles, such as the distance between stars, diameters of planets, craters on the moon—in fact, a precision device for determining the angular separation between two defined points in the field of the eyepiece of the telescope.

The filar micrometer comprises a box *A*, Figure 4, to which are screwed or brazed two tubes: one, *B*, to receive the eyepiece and the other, *C* (usually 1¼" diameter), to slide on the nose-piece of the telescope tube. Inside the box is a slotted plate *D*, sliding in accurately made ways (gibs), and fastened to it are two crosshairs at right angles to each other, of either spider web or metal wire. The plate is moved by a screw *E* of fine pitch, engaging the nut *F* attached to the above-mentioned plate. On the outer end of the micrometer screw is the knurled thumb wheel *G* and a graduated drum *H*. Back-lash is prevented by two coiled springs *I, I*, pressing against studs screwed to the slotted plate carrying the hairs.

The ocular must be a positive one, capable of being carefully focused on the crosshairs. A small lamp bulb *J* illuminates the hairs for night work, and is regulated for brightness either by a rheostat or by filters just inside the bulb.

If a micrometer screw of 40 threads per inch is used (these can be purchased from L. S. Starrett Co., Athol, Mass., or the Brown and Sharp Mfg. Co., Providence, R. I., or some other maker), then the drum is often divided into 25 major divisions, each division registering an advance of the plate which carries the hairs one thousandth of an inch. Subdivisions may be added. Usually the screws have finer threads than 40 pitch.

With a single micrometer the crosshair is set on one of the objects and

the division on the drum opposite the index K is noted. The hair is then advanced to the other object and the drum read again. It then remains only to ascertain the value (a constant) of one of the divisions in angular units, and to apply this factor to the difference between the two readings, in order to obtain the angle between the two points observed.

This method may suffice very well, say on Polaris, in measuring the angular separation of its companion, for the North Star would not move

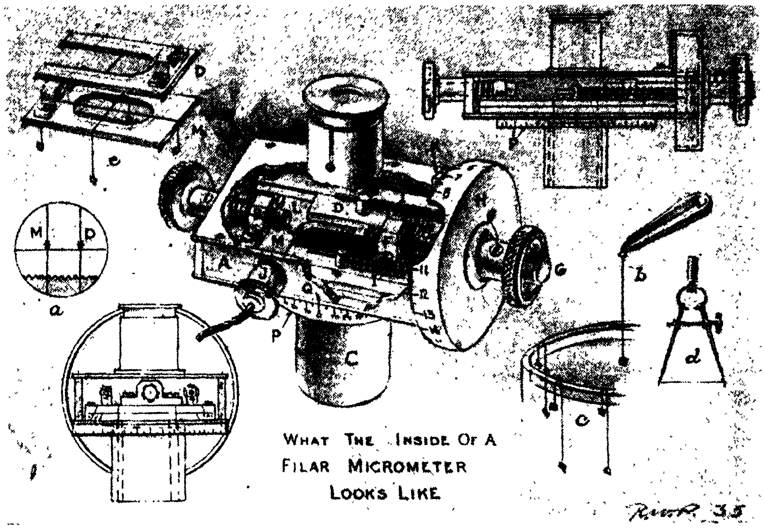


FIGURE 4

enough during the observation to introduce a serious error. But when objects are chosen near the equator, where they are moving rapidly in right ascension and probably not at the same rate as the driving clock, other methods are required. This can be overcome by the addition of another movable crosshair on a plate of its own, actuated by a screw at the other end of the box, at L. The procedure will now be as follows:

The two crosshairs are brought to bear on the two objects in the field of view (small drawing a, at left) with M setting on the left-hand star and D on the right. When the observer is satisfied that the bisection is good the division on the drum is read, D is turned until its hair is superposed over M, and the drum is read again. In order to permit him to keep track of the number of turns of the screw, a saw-toothed template is attached to the right-hand plate M, as shown at a (same small drawing) and M (drawing in upper, left-hand corner), having the same pitch as the screw. The number

of teeth is counted as the crosshair traverses them. Thus the whole number of turns ($1/40''$ each), plus the fraction given on the graduated drum, will give the total run. The result, multiplied by the angular factor value, gives the angle sought.

A filar micrometer often has a position circle. This circle *P*, will give the position angle of the line joining the two objects with the right ascension circle passing through the objects. First, rotate the box until, with the telescope at rest, a star will trail along the longitudinal hair. Read the position circle at index *Q*. Then, with the circle clamped to the telescope tube, rotate the box until the longitudinal hair bisects the two objects. The reading at *Q* will now be the position angle. This is an important reading in double star observations.

To make it: At best the whole device will be rather cumbersome, hence it is desirable to use as thin and light members as possible. The box should have side walls of brass or aluminum $1/8''$ to $3/32''$ thick, and top and bottom plates $1/16''$. Crosshair plates *D* and *M* should be $3/32''$, and their gibs the same. The knurled thumb wheel and drum should be turned up on the lathe as light as possible. All parts except the micrometer screw are of brass. No. 3-56 screws or smaller should be used for the gibs, and to fasten together the walls of the box.

In assembling and fitting, start with the lower box plate and adjust its gibs to an easy sliding fit. To facilitate this adjustment the screw holes in the gibs (on one of the gibs) may be a little oversize. Repeat the same operation for the upper plate. The nuts *F* and *R* have previously been fastened (brazed) to the plates. Then, with the nuts against the box walls, drill and ream the holes through both walls and nuts. Do this on the drill press, being careful to clamp the box to the drill press table, so that the plate ways are truly parallel with the drill. Before removing, replace the drill or reamer with the tap, and tap out the nuts. There must be no binding of the screw in its nut as the plate moves along the ways.

If spider lines are used for the crosshairs (tough spider cocoon may be obtained from C. L. Berger Sons, Roxbury, Mass.), pull out a piece of the spider line with tweezers and pinch on a tiny weight of lead, as shown at *b* (lower, right-hand drawing). Reverse and pinch on another weight at the other end. Before attaching the spider line to the plates the stretch must be taken out of it, otherwise it will buckle and become slack on damp days. Immerse the four spider lines, thus prepared, in water for a few hours by hanging them over the rim of a glass tumbler, as at *c;* or the line may be fastened to the legs of small dividers *d*, immersed in water and the legs opened slightly in order to take up the stretch. Prepare guide lines on plates *D* and *M* by scratching them in with a knife point, and hang the stretched lines over them as at *e* (upper left), securing them with a drop of shellac.

The above operation is a rather delicate one and will require steady hands. Nowadays very fine metal crosswires are coming into use because they are less breakable under sudden jars. I well remember trying to repair the

spider hairs in a transit well out on the polar ice pack, in latitude 83° North, with the temperature 50° below zero.

The hairs must be sunk sufficiently into the surface of the plates so that they will not interfere with each other as the one plate is moved across its mate, yet they must be so nearly in the same plane that they will both be in sharp focus in the eyepiece. The eyepiece is first focused on the cross-hairs, and then the entire micrometer is focused on the star.

Probably this instrument will not be very useful to the amateur, but it is an interesting mechanism to build, and if carefully made it is capable of remarkably fine performance.

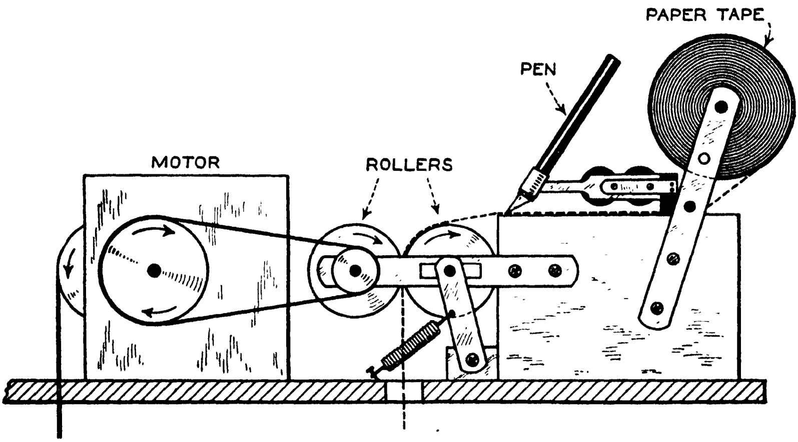
The value of the scale divisions, for the particular telescope it is used with, can be determined by several settings on fairly wide double stars whose separation is known, and the mean of a large number of observations taken as the final angular value.

A Simple Chronograph *

By W. T. Hay, F.R.A.S.
London, England

The chronograph described in this paper was the outcome of a suggestion made to me by Dr. W. H. Steavenson. He was of the opinion that a cheap, practical chronograph could be constructed from the standard mechanical components which can be purchased nowadays from toy shops, and he suggested the use of Meccano. At his request, therefore, I undertook the construction of a chronograph, utilizing only standard Meccano parts.

The completed article proved successful, but was too noisy in operation.



Drawings by J. F. Odenbach, after the originals in the *Journal B.A.A.*

Figure 1

Various expedients were tried in order to reduce the noise, including the suspension of the motor in an oil bath, without success.

Having previously constructed an efficient driving clock out of an old gramophone motor, I suggested making the chronograph motor on the same lines, retaining, so far as possible, Meccano parts for the remainder of the chronograph.

This method of construction proved to be cheap, efficient and perfectly silent in operation. In due course the completed chronograph was installed in Dr. Steavenson's observatory, where it is now giving satisfactory results.

I constructed a second model for my own observatory, and this model

* Reprinted by permission, from the *Journal of the British Astronomial Association*, Dec. 1932.

is identical in principle with Model No. 1, but embodies certain improvements in design and refinements in construction.

The chronograph under discussion differs from the usual observatory type in that the seconds are recorded on a paper tape, instead of on a drum.

The three essentials for a chronograph of this type are (1) the motor; (2) rollers for drawing the paper tape along under the fountain pen; and (3) the electric magnet for actuating the pen. These three essentials are shown in simplified form in Figure 1.

The motor consists of a gramophone motor from which the springs have

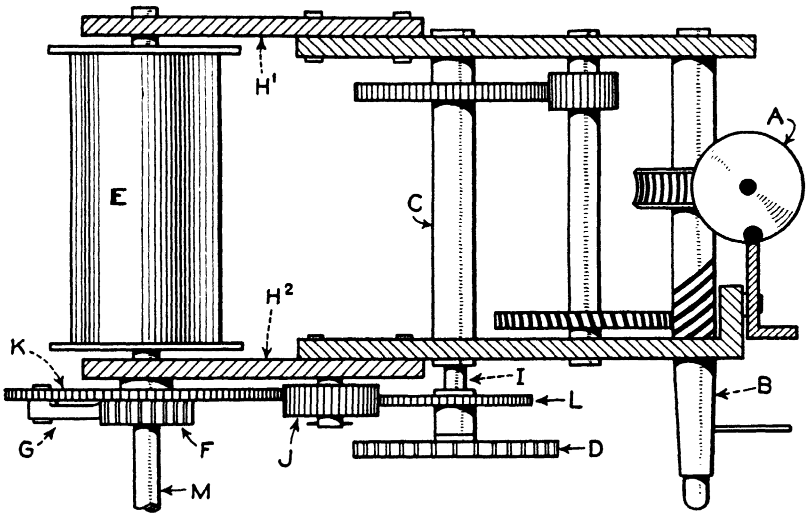


FIGURE 2

been removed, and to which is added simple gearing, and a cable drum, giving the motor a weight drive instead of the spring drive (Figure 2).

The spindle of the cable drum is carried by an extension to the existing frame of the motor, and this extension consists of two brass strips, 1″ in width, ⅛″ in thickness and about 4″ long. These strips are riveted or screwed to the side plates of the motor. Four feet, made of brass strip bent at right angles, are also fastened to the side plates by the existing screws.

The spindle *C*, which normally carries the spring drums, is drilled centrally at one end, and a smaller spindle is inserted and pinned. This smaller spindle carries the gear-wheel *L*, and the chain sprocket *D*.

A short spindle is screwed into the frame to carry a loose pinion *J*, which meshes with the gear-wheel *L*. A long spindle *M* also carries a large loose gear-wheel which meshes with the loose pinion *J*. A pawl is fixed to this

large gear-wheel K. The spindle M has fixed to it the cable drum E and the ratchet wheel F, and terminates in a handle for winding the cable on to the drum. On the weights rotating the drum, the large gear-wheel K is driven by the ratchet wheel and pawl, and in turn drives the loose pinion J, and through it the entire gearing of the mŏtor.

All the added gears, chain sprocket, ratchet and pawl are standard Meccano parts. A Meccano wooden roller, suitable for the drum E can

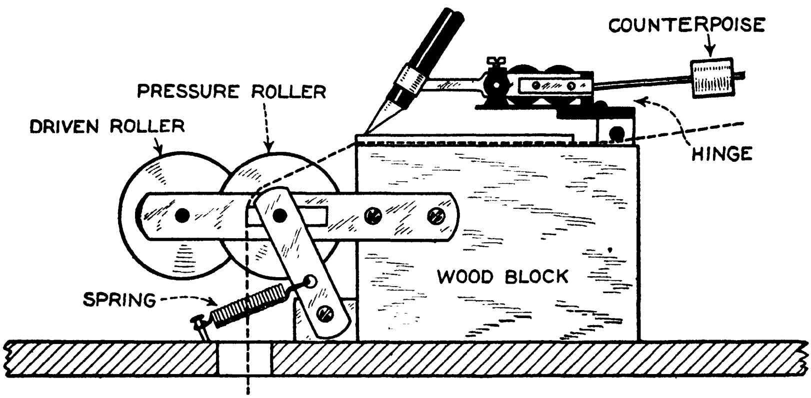


FIGURE 3

also be obtained. The motor can, therefore, be converted at the cost of a few shillings. Gramophone motors can be purchased quite cheaply nowadays, but an old motor with broken springs is ideal for the job, provided the governor is in good condition.

The two rollers are quite easy of construction, both being pieces cut from a wooden Meccano roller. They must be a shade wider than the paper tape, and should be faced with sheet-rubber seccotined on. One of these rollers should be provided with flanges to act as guides for the tape.

Meccano strip is used for mounting these rollers, and they are both fitted with short spindles, that which carries the driven roller being provided with a chain sprocket to take the drive from the motor. The other roller acts as a pressure roller and is held against the driven roller by coiled springs.

The rollers, electric magnet and supports for the roll of tape are all mounted on a block of wood, which is afterwards affixed to a baseboard (Figure 3).

The pen magnet is made from a cheap, small electric bell of the metal base type. The wiring is altered to make the armature give a dead beat instead of the usual tremolo action. A clip, soldered to the armature rod, takes the place of the hammer, and accommodates the fountain pen.

The base of the electric bell is hinged to the wooden block to permit the

pen being raised from the tape. It also allows the pressure of the pen on the tape to be adjusted by fitting a counterpoise to the base (Figure 3). The base must be raised so that the paper tape can freely pass along underneath the pen. Two small wooden blocks or a few washers will suffice, care being taken to see that there is room between the blocks for the tape.

Some kind of guide must be provided for the tape on the top of the wooden block. This can either consist of a few pins pushed into the block, or can be made more elaborately. Various methods will suggest themselves to the constructor. Two Meccano strips fastened to the block act as a support for the roll of paper tape.

A feature of this chronograph is its independence of a clock for providing the seconds beats. A small rod inserted in, or soldered to the spindle

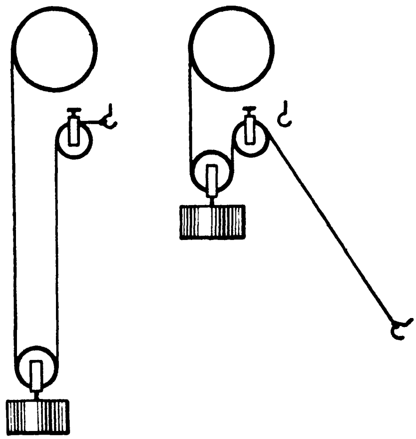


FIGURE 4

B (Figure 2) can be made to brush against a copper-foil plate at each revolution, and its rate can be adjusted to mean-time seconds or sidereal seconds by the ordinary gramophone motor governor.

On Dr. Steavenson's instrument the seconds impulses are now given to the pen by his Cooke clock, through a mercury-trough contact on the pendulum, and the pen on my own instrument is actuated by a Synchronome clock through a relay.

A hand-switch connected to the instrument by flex-wiring will close the circuit and actuate the pen at will. The spacing of the seconds ticks on the tape can be varied by the use of differently sized chain wheels, and observations can be timed to one-tenth of a second, or even less.

As the motor has no maintaining gear, I find it possible to get a run of about an hour by using the method of attaching the cable shown in Figure 4.

The free end of the cable is attached to a hook. When the weights have nearly reached floor level the free end of the cable is unhooked and the weights pulled up to the top without altering the rate of the motor; the free end of the cable is then attached to another convenient hook.

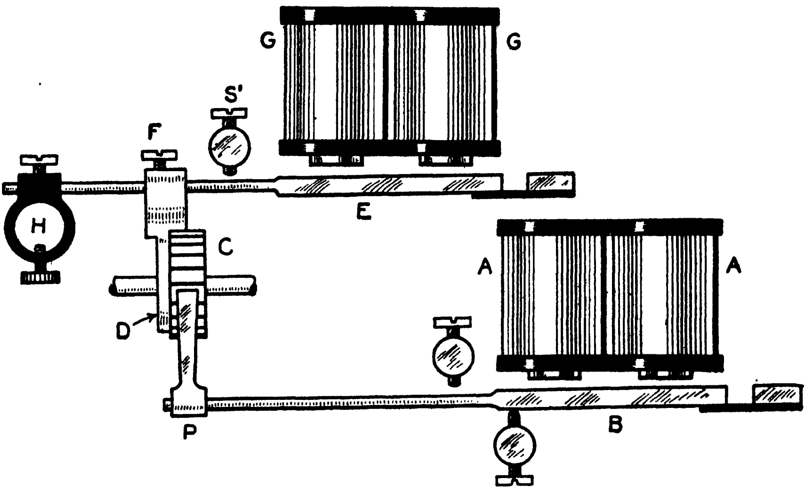


FIGURE 5

[EDITOR'S NOTE: Two years after the above paper was published, the following one by the same author appeared in the same journal (June 1934), and this too is presented.]

The subject of this paper is an improvement to the chronograph described in the *B. A. A. J.*, 43, 80–84.

It consists of a simple device which automatically divides the seconds ticks on the paper-tape record into groups of ten, thereby facilitating the reading of the tape record. The time and labor-saving properties of this device will be appreciated by those who have used the earlier type of chronograph previously described.

The accompanying drawing (Figure 5) shows the design of the apparatus, which consists of a coil-magnet with pen-carrying armature, *GG* and *E*, similar to that on the earlier model.

In addition, however, there is a second coil-magnet *AA* and armature *B*. This magnet is operated by the clock-contact at every second and the forward movement of its armature rotates a 20-toothed ratchet wheel *C* one tooth at each beat, by means of the pawl *P*. The ratchet wheel in turn pushes the pen-armature *E* through the rocker *F*. In effect, both arma-

tures, *B* and *E*, move together, *B* being moved electrically, and *E* being moved mechanically by *B*.

The counting device (Figure 6) is simply a disk fastened to one side of the ratchet wheel. This disk is of slightly less diameter than the ratchet wheel, the teeth of which project only slightly beyond the disk. Thus, when a tooth of the wheel pushes *F* forward (making the pen stroke) *F* returns to rest against the disk.

The disk, however, is cut away at two places (corresponding to ten teeth) to the depth of the tooth and therefore allows *F* to make a longer stroke at these two points. The resulting track is shown beneath Figure 6.

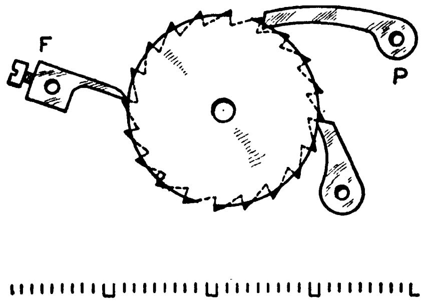


FIGURE 6

The coils *GG* (Figure 5) are connected to the battery and a hand-switch, so that the pen-armature can be moved at any time, to record an observation, independently of the counting mechanism.

Variations can be made in constructing this model. For instance, the ratchet wheel can have 30 teeth and the disk 3 slots, one a little deeper than the other two. This would record half-minutes in addition to ten seconds. On my own models I use a 20-toothed wheel which is an ordinary Meccano ratchet wheel.

The length of the pen-stroke depends on the amount of tooth projecting beyond the disk and this should be very small, certainly not more than 1/32″. The length of the stroke can be varied a little, however, by sliding the pen-holder *H* along the armature rod.

The slots in the disk should not be more than 1/32″ in depth. Both armature rods should be stiff, with no flexure, and the springs of the armatures should not be too stiff. The spring on the pawl should be weak, but the ratchet should have a strong spring to prevent overjumping. A piece of fairly stiff spring brass will suffice for the ratchet and spring combined.

The ratchet wheel should run free on its spindle, which should be a good sliding fit in the wheel.

The stop *S′* (Figure 5) should be adjusted so that *E* does not touch it

except when GG are operated by the hand-switch, and it must have sufficient clearance to allow F to escape from the ratchet wheel teeth.

The coils AA should be mounted high enough to bring the pawl on a level with the top of the ratchet wheel. Coils GG should be mounted so that the armature rod E is central with the ratchet wheel. The rocker F should be inclined downward.

As it requires a fair amount of power to operate the ratchet wheel the coils AA should be of fairly low resistance. Ordinary bell coils will do. As the coils GG only come into operation when it is desired to make an observation record one bell coil would no doubt be sufficient to work the pen-armature by the hand-switch.

Should it be intended to operate this chronograph from a Synchronome clock the coils AA must be of the same resistance as the clock coils if they are to be included in the wiring circuit of the clock. In my own instrument the coils AA are cheap bell coils but are worked by a separate battery through a relay operated by the Synchronome clock and the relay has a Synchronome clock coil.

On no account must the coils GG be connected into a Synchronome clock circuit, as the operation of the hand-switch would also move the clock forward. They must be connected to a local battery and the hand-switch.

The Evaporation Process for Coating Astronomical Mirrors

By JOHN STRONG
Senior Research Fellow in Astrophysics, The California Institute of Technology

The present chapter has as its purpose the description of the equipment needed to produce reflecting films on astronomical mirrors by the evaporation process. The equipment described may not be the most economical which could be made to give satisfactory results, but it would be difficult for me to give reliable directions for doing this work with less, since I have worked only with the standard equipment customarily used in research work where high vacuum is required. However, in giving directions for carrying out the process, I shall attempt to indicate experiments which may be of interest to amateurs who wish to try evaporating.

I shall also describe some developments which have come out of our work here at the California Institute of Technology. There are, undoubtedly more developments to be made and, although some of this work is not exactly astronomical in character, it has had to do with the improvement of astronomical instruments.

The present material is meant to supplement articles on this subject already published:

1. C. Hawley Cartwright and John Strong, *Review of Scientific Instruments*, Vol. 2, pp. 189–193 (1931)
2. John Strong, *Publications of the Astronomical Society of the Pacific*, Vol. 46, pp. 18–26 (1934)
3. John Strong, *Astrophysical Journal*, Vol. 83, pp. 401–424 (June 1936)
4. John Strong and E. Gaviola, *Journal of the Optical Society of America*, April 1936

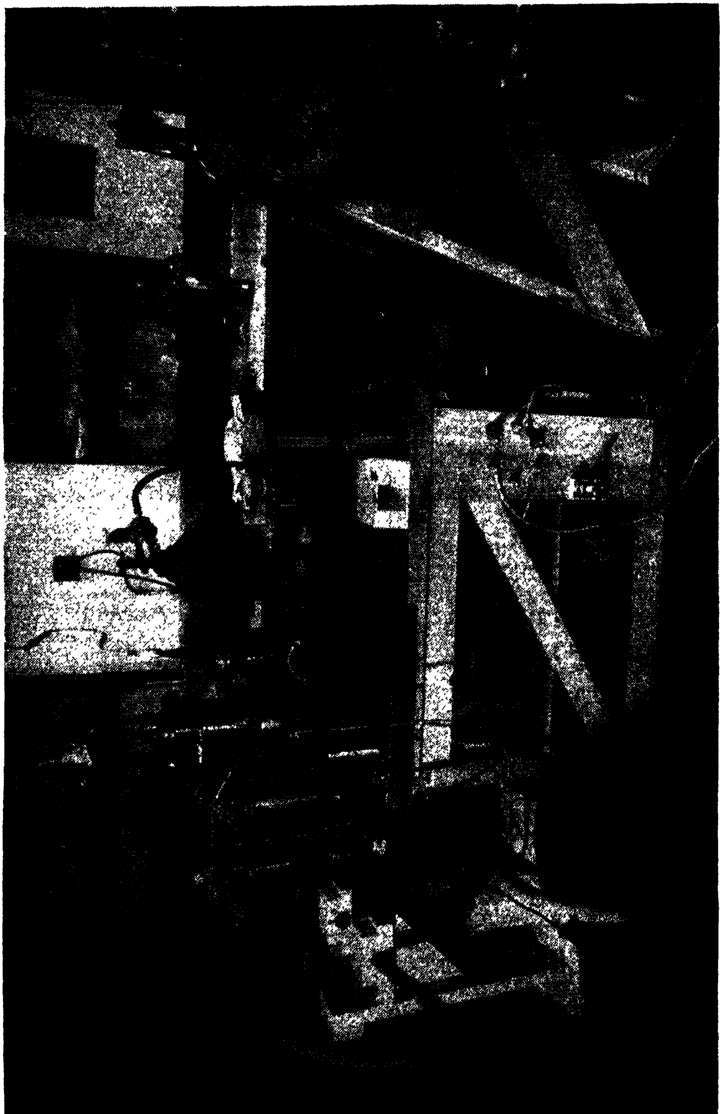
Other pertinent articles include:

5. C. Hawley Cartwright, *Review of Scientific Instruments*, Vol. 3, pp. 298–304 (1932)
6. Hiram W. Edwards, *Review of Scientific Instruments*, Vol. 4, p. 449 (1933)
7. Robley C. Williams, *Physical Review*, Vol. 46, p. 146 (1934)
8. John Strong, *Journal of the Optical Society of America*, Jan. 1936, pp. 73–74.

A very valuable review on the subject, entitled "Metallic Surfaces and Thin Films, with Particular Reference to Aluminium," has been prepared by Miss W. Lewis of the British Aluminium Co. It will be possible to obtain a copy of this work gratis by writing directly to The Intelligence Department, British Aluminium Company, Limited, Adelaide, King William Street, London, E.C. 4., England.

Equipment: The most convenient arrangement of evaporation chamber consists of a base plate which communicates with the pumps and has about six electrodes for supplying filament current and one for the high potential cleaning discharge.

The equipment I am at present using is shown in the photograph (Figure 1). The six terminals are wired to a switchboard in order to facilitate



the making of the connections. The filaments may be mounted on the electrodes. The mirror may be mounted vertically on the base plate or supported above the filaments. The whole arrangement is covered by a glass bell jar or, better yet for bigger mirrors, a metal bell jar. Examples of each are shown in the photograph. The jar is sealed around the base by a mixture of beeswax and resin (2 parts wax to 1 resin). This is applied smoking hot, with a medicine dropper. The wax has the very important property of sticking to a cold steel or brass surface. The wax is removed, after the evaporation, by means of a putty knife. When all of the wax that can be so removed is taken away, the joint is broken by a slap of the hand on the top of the glass jar or, in the case of the metal jar, by prying with a screw driver. Of course, one must not try this until air is admitted into the jar.

The pipe connections to the base of the jar and the electrical inlets must not leak. It is important to emphasize that a leak in vacuum work is vastly more serious than in other cases. The reason is simple. If a cubic millimeter of gas leaks into the apparatus in a given length of time and the pressure is sufficient for evaporation—say 10^{-4} mm of mercury—the gas will expand $\left(\frac{760}{10^{-4}}\right)$ or about 8 million fold, giving not a cubic millimeter for the pumps to handle but the volume corresponding to that of a cube 20 centimeters on an edge.

The joints of the pumping line may be soldered, silver-soldered or welded. In this latter case they should be gas welded or, if electric welded, shielded electrodes should be used.

In case steel is used I have found a procedure which seals all fine leaks which may exist, and at the same time exposes a surface to the vacuum

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FIGURE 1

On facing page: Apparatus for preparing metallic films by vacuum evaporation.

At the lower right is shown a glass bell jar with cleaning electrode at top.

Directly above is a cast aluminum alloy bell jar, and inside this is a chuck for holding mirror's face downward for aluminizing. The shadow indicates the size and shape of the last mirror aluminized.

At center is shown a 1" steel base plate with electrodes protruding.

Behind is a hydrogen tank that is used when sputtering.

At left is a spark coil used for vacuum testing and cleaning. At the time this photograph was taken the coil was connected to the glass discharge tube, for vacuum testing.

Above the coil is a by-pass valve of 4" diameter, for isolating the 6" and 2¾" diffusion pumps at the left, when the apparatus is taken apart.

Between the valve and the 6" pump is a liquid air trap to be used in special cases.

Hypervac mechanical pumps are shown at the lower left.

Between the 2¾" diffusion pump and the mechanical pump is a trap for water vapor, made of glass and cooled with liquid air.

Below the base plate is a switchboard to facilitate connections to the transformer, as shown.

Above the transformer is a lamp and the scale of the Knudsen vacuum manometer connected by a glass valve above the switchboard.

A 6" mirror that has just been aluminized in the glass jar, is shown at the right of the valve.

This picture was taken by O. S. Marshall, with a wide angle lens, and the latter accounts for the apparent distortion.

which does not give off gas. The procedure is, simply, after cleaning all ordinary grease from the inside (a substance that is absolutely taboo in vacuum equipment, anyway) it is coated with a special low vapor pressure wax, Apiezon W. This may be obtained from James G. Biddle Co. of Philadelphia, for about $1.00 per lb. (1936).

If this wax is not used it is advisable to put air pressure in the equipment (the bell jar will fly off, so it is best to bolt a specially made metal covering which just encloses the electrodes down to the base plate) and hunt out any leaks with soap solution. These are to be repaired, of course. Finally, to close the very smallest ones not detected by the soap solution it is advisable to coat the outside with Glyptal lacquer. I paint on three layers, first machine blue, then red and finally blue again. This makes it easy to insure complete coverage with each coat.

As for the electrical connections through the base plate, these may be ⅜″ brass screws with washers and a nut on the inside. The insulation of these is effected by mica washers under each of the brass washers and a piece of thin strip mica rolled around the screw. The hole in the base plate is about 7/16″ to give clearance for this. Electrical wires of rather large diameter—about No. 9 copper wire—can be soldered in the screw slots on the outside, for the connections.

The nut is brought home and the insulation tested with a lamp circuit. After all six leads are in place hot beeswax and resin is flowed over the heads and washers on the bottom. For this the base plate is placed in an inverted position. Later, on suspicion of leaks, this may be painted with thick shellac. Any connection desired may be made to the screws on the inside.

The glass bell shown in Figure 1 has a hole bored in the top for an electrode. An alternative procedure is to get a bell equipped with a hole. This may be covered with a metal plate sealed with the beeswax-resin mixture, as previously described.

A three- or five-gallon glass bottle with the base cut off and ground makes a good jar, the hole allowing entrance for the cleaning electrode. One should be careful, however, to choose a strong one, as it would be dangerous if it collapsed under vacuum.

The electrode for cleaning may be led through the base plate in a capillary glass tube.

The use of this cleaning electrode will be described later.

I have attached a Knudsen vacuum gauge to my bell. This is not absolutely necessary, although it is very useful.

Also, I have equipped my tank for sputtering. For some metal films, such as the platinum metals, sputtering is more convenient than evaporation.

The pumps will afford, without a doubt, the most difficult problem for those who wish to evaporate.

The pumping requirements will be met best by the use of a Hypervac pump in conjunction with an Apiezon oil diffusion pump. The former is manufactured by the Central Scientific Co. and the cost is relatively high.

A Megavac will do as well for most purposes, however, and it is less expensive. If the system is absolutely tight a Hyvac pump will suffice. If a Hyvac is used it is best to have two or even three stages in the diffusion pump. The Apiezon oil diffusion pumps may be constructed from brass with the help of a lathe and silver soldering outfit. It will be best, however, to buy them directly (James G. Biddle). No liquid air trap is needed in connection with their use, as with mercury diffusion pumps.

I have equipped my pumping system with by-pass valves so that I can coat a mirror and then open the jar for reloading without destroying the

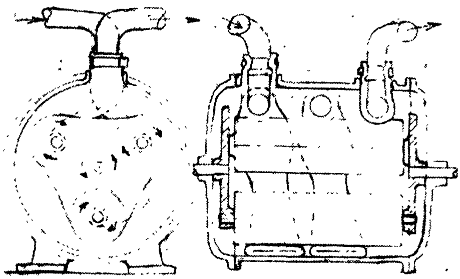


FIGURE 2

An idea for a force pump. It has not, however, been actually tested. Similar ideas have no doubt occurred to others.

vacuum in the pumps. With it I can open up, recharge, evacuate and fire a new "batch" of mirrors in half an hour. When it is necessary to cool down the pumps before admitting air, much time is lost, and the oil absorbs gas.

The use of a Hyvac oil pump and a charcoal tube (absorbent charcoal) that can be cooled to liquid air temperatures affords another way of obtaining high vacuum. This method is described in articles No. 1 and 8. The jar and charcoal tube are first thoroughly evacuated by this method with the Hyvac, the charcoal being heated to about 400° C. Then the pump connection is sealed off and the charcoal is cooled to liquid air temperatures. An ordinary spark discharge tube connected to the jar soon gets hard; that is, it will not pass a discharge when connected, for example, in parallel with a 1" spark gap. The cleaning electrode, or a discharge tube, will suffice for this test. The alternate gap starts to pass the discharge when the vacuum is around 10^{-3} mm mercury pressure—although this varies for different discharge tubes. When such a vacuum is attained, evaporation may be started, although a higher degree of vacuum (10^{-4} to 10^{-5} mm of mercury pressure) is desirable. It is well to let the jar "soak" for a time—say for an hour at this vacuum, in order to allow it to "outgas." Otherwise, when evaporation starts, a surge of gas from the exposed sur-

faces may drive the pressure up and give an unsatisfactory film (exhibits bloom or in extreme cases is as black as soot).

In any case it is important to avoid leaks. If one has trouble he must think first of leaks. If the vacuum pumping is working properly one can let a few cubic millimeters of air into the jar through a stopcock and it will disappear in a minute or so, as shown by the discharge across the alternate spark gap.

The equipment, including mirror supports, filament connections, etc., should be made of brass, copper, nickel-plated brass, or nickel. Iron and steel give off gas until they have aged in the vacuum for some time. However, as I have pointed out before, a lining of Apiezon wax-W avoids this. It may be applied to the pump connections and the bell jar. The base plate can be bare aged steel or it could be electroplated. For best results from the start, however, I would suggest brass. It should be about 1″ thick.

I have evaporated successfully in a "bottle" bell jar with a charcoal tube cooled with "Dry Ice," using a Hyvac mechanical pump. Also, I have successfully used a water aspirator to get the preliminary vacuum, and then liquid air on the charcoal. Someone may do some experiments to determine whether it is possible to evaporate successfully with a water aspirator and Dry Ice as refrigerant. The former costs about $2.50 and the other 10¢ per lb. (1936).

Mr. William Van Dorn has sketched a mechanical pump made of a rubber hose. He and I invented this independently, although I doubt whether the principle on which it operates is new. However, we leave it to some experimenter to test out.

The source of power required for evaporation is 110 volts for the pumps and 0–30 volts for the evaporation coils. A "Little Jeff Toy Transformer," rated at 150 watts, is a good source of these lower voltages. The seasoned experimenter will realize that 150 watts may mean anything up to 1 KW for a short time.

One will need a supply of 30 mil tungsten wire. This is obtainable from the Fansteel Corporation, of North Chicago. The wire is wound hot into coils of ten turns, pitched 4 turns per inch on a 5/16″ mandril. One coil is enough to coat a 6″ mirror when it is charged with one "U" of 1/32″ aluminum wire on each turn. The length of wire in each turn is about 4/10″. The coil may be fired to melt down the aluminum in a preliminary run before the mirror is put in the bell jar. Twenty volts applied to the coil for 4 or 5 seconds are required for this. The metal will all evaporate if 20 volts are applied for 15 to 20 seconds.

For silver and other metals a helical spiral which converges to a point makes a cup-like container in which metal is evaporated. Even when the metal melts it will hang in the coil, due to surface tension.

Another method of heating the aluminum is in a hollowed-out cavity in a 1/4″ carbon (non-cored type). A few turns of very heavy copper cable about the core of a 1-KW Thordarson high tension transformer will give a high

current low voltage supply suitable for heating this. The aluminum is evaporated upward from the cavity in the carbon.

For further information see the articles already published on this subject.

Procedure: The mirrors must be as clean for aluminizing as for silvering. Not only this, but they must be dry. To get a mirror both clean and dry is more difficult than just getting it clean. If it is dried with absorbent cotton, and especially if the edges are not absolutely free from pitch, it is likely that it will not be clean enough. If it is aluminized in this condition a coat may be obtained which appears perfect at first but which will develop countless tiny blisters in a day or so. This is caused probably by gas liberated in a chemical reaction between the aluminum and the surface contamination on the mirror face. A coat of aluminum on clean glass, on the other hand, adheres so well that it cannot be stripped off with adhesive tape.

The first step, then, in cleaning a mirror on the face to be coated is to clean its sides and back entirely free from pitch and rouge. For this, nothing is quite as effective as an ordinary ink eraser which contains an abrasive. Then it should be cleaned as for silvering, except that it is treated last with the acid. After rinsing with distilled water it is set on edge to dry on the filter paper or a very clean towel. The hands and fingers should not touch the edge. When dry it is rubbed with absorbent cotton until the breath condenses to form a structureless gray film.

When the mirror is in the bell jar, and as this is being evacuated, one passes a glow discharge between the aforementioned electrode and the jar, in order to effect the final cleaning. A Ford spark coil would be satisfactory for this.

It is best to mount mirrors face down in the aluminizing chamber, although we do not do this with the big ones, for obvious reasons.

One coil at 12″ distance and opposite the center is sufficient for a 6″ mirror. The coils should be distributed to give a uniform coat for larger mirrors.

If the coat scatters light (bloom) the vacuum was not high enough during the evaporation.

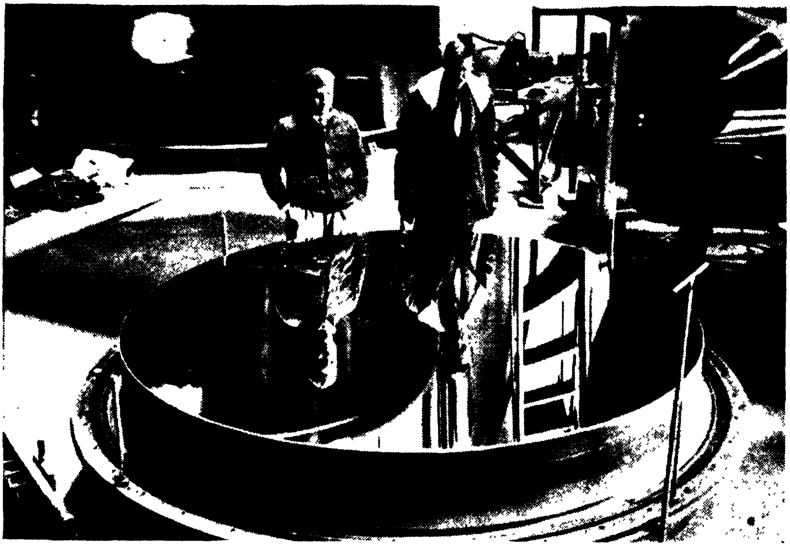
As I have stated before, the standard source of aluminum vapor is a helix each turn of which is charged with an aluminum U. The amateur may test out iron heaters, crucibles, high frequency heating and other ways of getting the aluminum to vaporize. One possible way is to explode an aluminum wire by means of a condenser discharge.

I have given reference to the papers (No. 4) describing the use of nonuniform films of aluminum for parabolizing, figuring and hyperbolizing mirrors. The amateur who succeeds in building a workable apparatus will find these applications of interest.

The evaporation of thin films of fluorite, to decrease the reflection of glass with the possibility of application to fast cameras in order to increase their transmission and control halation is one of the developments which have come out of this work—see reference 8.

One can also prepare half-reflecting films for color cameras—wedge filters, Fabry-Perot plates, etc.

Anyone who starts to aluminize with good equipment will soon learn the minor "tricks," which I have not taken space to describe, and it is likely that he may go beyond the present state of the art and contribute something new. With planning, the expense of building the appartus could, no doubt, be materially reduced. However, one might point out that sputtering has been done for many years, yet the equipment for this work is still expensive. With evaporation this will probably be even more true.



Science Service Photo

The 100" mirror just after the author of the present chapter had aluminized it in 1935. He stands without a hat. The other figure is Dr. Enrique Gaviola, the author of the chapter entitled "Foucault's Shadows," in the present volume.

[EDITOR'S NOTE: As stated in the *Astrophysical Journal,* Vol. 83, page 422, the author of the preceding chapter was the first to coat an astronomical mirror by the evaporation process, and was the first to discover a practical technic for the use of aluminum. The aluminum to be evaporated is hung in small pieces on helical coils of tungsten wire opposite the mirror, and is vaporized when these coils are heated to whiteness by the passage through them of an electric current.

However, if the air were not first pumped out of the containing vessel, the atoms of vaporized metal would collide with molecules of air and be stopped instead of reaching the glass. To prevent this it is necessary to evacuate the vessel to about one ten millionth of normal atmospheric pressure. This is best done in two stages, by means of two separate types of

pumps. First the fore pump, which works on a mechanical principle, reduces the pressure to about ten one millionths of atmospheric pressure, mechanical pumps working most efficiently only down to a certain pressure. Then a diffusion pump, having no moving parts but working more efficiently at extremely low pressure, is connected between the mechanical pump and vacuum vessel and is started. This completes the work. As the reader will have noted, the author recommends as fore pumps either the Hypervac, Megavac or Hyvac pump, and as a diffusion pump the Apiezon oil diffusion type. To give at least a rough general idea of the price range for such apparatus, the Central Scientific Company's prices, as of 1935, were as follows: Hypervac, with 110-v. A.C. motor, \$300; Megavac, with 110-v. A.C. motor, \$155; Hyvac, with 110-v. A.C. motor, \$75. Future prices are, of course, subject to change. The James G. Biddle Company's price for Type P oil diffusion pumps of all-metal construction, using Apiezon oil and including necessary accessories but not a backing pump (same thing as a fore pump), was approximately \$205 (1935. Future prices subject to change).

The principle on which the diffusion pump works was stated by Langmuir in U. S. Patent 1,393,550: "I cause a high velocity stream of mercury vapor to flow through a tube toward a condensing chamber, and arrange the apparatus in such a way that a portion of the path of this stream communicates with the vessel to be exhausted." The working principle is parallel with that employed in the jet or ejector type of water pump widely used for keeping leaky cellars dry: a stream of water shoots out in a jet, and carries along with it the surrounding water molecules. Just as the water molecules in the water pump are struck by other water molecules and literally bumped along, so in the mercury diffusion pump molecules of mercury vapor bump and remove molecules of the aïr to be exhausted. The oil diffusion pump, invented by author of the chapter on the Zernike test, C. R. Burch (British Patent 346,293), uses vaporized oil in place of vaporized mercury. In a letter, Mr. Strong points out that "If someone is ambitious enough to start evaporating, he will probably find the construction of his own diffusion pump both feasible and economical and," he adds, "an excellent design is by Sloan, Thornton, and Jenkins, in the *Review of Scientific Instruments,* March 1935."

When the aluminum coating has been deposited, and as soon as the metal makes contact with the air, a film of oxide—presumably corundum, Al_2O_3, or bauxite, $Al_2O_3 \cdot 2H_2O$—begins to form. This is very tough, being the equivalent of sapphire. Such coats may be washed with good soap when they become dirty, using distilled water and rinsing with distilled water, but even better is Alphasol O T, made by the American Cyanamid and Chemical Corporation, with offices at 30 Rockefeller Plaza, New York City, address Mr. Rose. Two ounces of the dry form will cost something under a dollar (1936).

Additional information about the aluminizing process may be obtained by reading the articles cited by the author in his footnote list, but from time to time the publishers receive requests for "*full* and *complete* instructions that start from the very beginning and take nothing for granted." Re-

gretfully it must be said that no instructions of this sort exist anywhere in print. A large part of the work is ordinary physical laboratory technic, and the physicist himself learns this at least partly by observation from other physicists. Some of it is to be described in a book in preparation by the author of the present chapter. Most of those who wish to try aluminizing will, however, have had some laboratory experience. To others one of the greatest difficulties to overcome possibly will be connected with high vacuum technic. Air molecules exhibit an astounding amount of ingenuity at crashing the gate, even after they have been bounced once or twice before. They almost seem to enter where nothing can possibly enter.]

Having to Do with Silvering—a Composite Chapter

Silvering of Telescope Mirrors in the Tropics—F. O'B. Ellison's method: Make the following solutions with distilled water.

(1) Silver nitrate 8 percent, pure crystals or A.R. [Analytical Reagent, similar to C.P.—*Ed.*].
(2) Ammonia solution specific gravity 0.984 (1 part .880 ammonia to 7 of water is about right).
(3) Pure caustic soda, or potash 3.125 percent (1 in 32)
(4) Pure glucose 3.125 percent (1 in 32).
If used immediately, may be dissolved in water only. If required to keep, must be dissolved in a mixture of alcohol 1 part, water 7 parts. Rectified spirit must be used—not commercial methylated.

All the reagents must be free from chlorides and the caustic soda should not contain more than traces of carbonate. Therefore ends of bottles, either solid or solution, should not be used.

To mix the silvering bath, measure out in separate vessels equal parts of 1, 2, 3, and 4. Pour some 2 into the whole of 1 until, on stirring well, the dark precipitate first formed is completely dissolved. Then add some 3, and stir well till a slight dark precipitate appears. Pour in some more 2 until this precipitate is dissolved. Then add more 3 again until a precipitate appears which does not dissolve on stirring. Clear this with more 2, and go on until all the 3 has been added. If there is now some precipitate, clear with 2 until the mixture is quite clear or only shows a slight yellow or muddy turbidity. There should not be a black precipitate, and probably the mixture will be absolutely clear before all of solution 2 is used up.

The remainder may be discarded.

Have the mirror fixed with pitch to a support, and with the surface to be silvered well cleaned with nitric acid, washed and suspended face down in some distilled water.

Put the whole of 4 into the silvering dish, pour in the mixture of 1, 2 and 3, and immediately immerse the mirror face down, and see that no air is caught under it. The mixture will rapidly turn brown and black: rock the mirror gently from time to time. See that its face clears the bottom of the dish by about half an inch.

At a temperature of about 80° F. the silvering will be finished in 10 minutes. A silvery scum often forms on the surface of the silvering solution between the edge of the mirror and the edge of the dish. This shows that the process is going on properly.

Have some hot distilled water, just too hot for the hand, in a wash bottle, take the mirror out and sluice it well with water under a tap. Then wash it well with the hot distilled water and dry quickly in a warm place. Polish with rouge in the usual way. One such bath should give a thick, opaque film through which the sun cannot be seen, and which, after polishing, should not show more than a few pinholes.—*F. O'B. E., Colombo, Ceylon.*

[F. O'B. Ellison is a brother of Wm. F. A. Ellison of Northern Ireland. —*Ed.*]

Recovery of Silver Waste Residues: James Stokley, Director of the Fels Planetarium of The Franklin Institute, Philadelphia, contributes the following:

In the Museum of The Franklin Institute there are many reflecting surfaces that must be resilvered three or four times a year, until it will be possible to have them aluminized. These include the 24″ mirror, secondary and Newtonian mirrors of the large reflector, a small pair of flats, and a large 18″ x 24″ flat, used with the 85′ focus solar telescope, and numerous small pieces.

With the aid of Dr. Nicol H. Smith, Associate Director of the Franklin Institute, in charge of chemistry, the astronomical staff has developed a method of recovering the silver nitrate from the spent silvering solution. So successful was this process that on the first attempt a pound of silver nitrate was recovered from the spent solutions that initially involved 1½ pounds of silver nitrate. The method of recovery is as follows, and the amounts given are for one pound of silver nitrate:

To the spent silvering solution, add hydrochloric acid until the solution is slightly acid (This makes the solution safe and it may be kept indefinitely).

Filter, and add a pint of water to the precipitate.

Boil the precipitate with seven ounces of potassium hydroxide and 12 ounces of sugar for about three-quarters of an hour, stirring vigorously to hasten the reaction. A grayish brown precipitate, consisting of silver and silver oxide with some impurities, will come down.

Wash this precipitate by decantation about ten times; using distilled water the last two times.

Dissolve the precipitate in eight ounces of nitric acid (sp.gr. 1.42–1.40) diluted with an equal amount of water. Heat this to hasten and complete the reaction.

Filter, and add enough water to the filtrate to make about 32 ounces. This is now a dilute solution of fairly pure silver nitrate.

Heat this solution to boiling and add four or five ounces of ammonium formate. Again a grayish brown precipitate of silver and silver oxide will form. This precipitate does not contain any impurities.

Wash the precipitate in distilled water by decantation.

Dissolve the precipitate in eight ounces of nitric acid (again diluted 1 to 1) and filter after the precipitate is dissolved.

Evaporate the filtrate to crystallization. The crystals are pure silver nitrate and should be kept in an air-tight bottle.

The cost of the chemicals involved was—

Seven ounces potassium hydroxide....	.40
Twelve " sugar..................	.05
One pound nitric acid.............	.60
Five ounces ammonium formate......	.50
Total	$1.55

A total of $1.55 has been spent on chemicals and over $10.00 worth of silver nitrate recovered, a substantial saving. Of course, the amateur may not have a pound of silver nitrate to recover, but he may use the proper proportions of the chemicals involved to recover the silver nitrate that he has used.

Recovery of Silver Waste Residues, by Dr. S. H. Sheib: In the silvering of mirrors only an infinitesimally small quantity of the silver employed is actually deposited on the glass in useful form, by far the larger quantity remaining behind, partly as a spongy sludge of metallic silver, and partly in the form of soluble silver compounds, some of which may yield explosive products unless promptly treated or otherwise disposed of. Where silvering is performed with sufficient frequency to justify the small cost, the silver in the waste residues which accumulate over an extended period may be recovered as follows:

Immediately after silvering, the spent silver solution and sludge is transferred to a large wide-mouthed jar and a sufficient quantity of a solution of common salt in water is added to convert all soluble silver compounds into chloride, which settles out in a dense white cloud. After this precipitate has completely subsided, leaving the upper stratum of the liquid clear, test by adding a further quantity of salt solution, and if a precipitate again appears, add a substantial quantity of the salt solution and allow to settle once more. Repeat the test and addition of salt solution until the failure of a precipitate to form shows that all soluble silver has been precipitated. There is now no danger of explosion and the jar and its contents may be set aside indefinitely. As fresh silver wastes collect, they are added to the contents of the jar and the mixture is then treated with salt solution, each time the new wastes are added, in the manner above described. The clear liquid which remains above the sedimented silver residues in the jar may be poured off from time to time to make room for fresh silver wastes. The residue consists of metallic silver and silver chloride, and darkens in color on exposure to light, but this in no way affects its value.

When a considerable quantity of the residue has collected, pour off the clear liquid as completely as possible and transfer the solid residue to a flat-bottomed glass or porcelain dish, drain off any excess liquid, spread out the residue in an even layer, and place the dish and its contents in a warm location to dry thoroughly. When dry, mix the residue with thrice its bulk of a mixture of potassium carbonate and sodium carbonate in equal parts, transfer the mixture to a sand-clay assay crucible, and heat in a hot coke fire, or in a gas furnace, until the mass is thoroughly melted and has settled into quiet fusion. A bright red to white heat will be necessary. Remove the crucible from the fire and allow it to cool. Break out the button of metallic silver, and wash it free from adhering salts.

Dissolve the silver button in nitric acid in a porcelain dish, and evaporate the solution to dryness over a vessel of boiling water. The residue of silver nitrate is transferred at once to a brown bottle to prevent deleterious effects

of light, and is sealed with paraffin to exclude chlorides and sulphur compounds which also affect it injuriously.—*Richmond, Virginia.*

The Deterioration of Silvered Glass Mirrors and the Reflecting Power of Polished Chromium Steel,[1] *by R. K. Young and Mrs. V. Krotkov:* The efficiency of a reflecting telescope depends upon the state of the silvered mirror. The glass must be resilvered at intervals which may vary from a month to a year, depending upon the climate in which the telescope is used and the quality of the silver coat. In a smoky city, where the air is charged with dust and chemicals, the mirror will tarnish very quickly, while in a clear dry air free from impurities it may last for a year or more.

Silvering small mirrors is a simple matter but the labor is much greater for larger sizes. In an observatory where the observers and astronomers do their own silvering, the task is often, under the pressure of work, deferred for some time after it should have been done. The present measures were made to correlate the change in appearance of the mirror with the reflecting power, in order that the observer might be able to tell to some degree how much loss of light there was.

In table I, columns 2 and 3, is given the reflecting power of silver on glass, as taken from the *International Critical Tables* and from values given by Langley. The latter were taken from a paper published by H. D. Curtis.[2]

TABLE I

λ	International Critical Tables	Langley	No. 1 New	No. 4 New	No. 1 Old	Chrominum
8000	96.3%	%	%	%	%	%
7000	94.6			93		
6000	92.6	93	90	89	86	69
5000	91.3	89	80	82	75	69
4500	90.5	85	74	78	63	68
4000	83.6	79	60	65	50	65
3500	67.5	61				

We may assume that these measures were made on very good silver coats. Nevertheless they differ by more than 6 percent at λ3500. Apparently a silver coat may look first class and yet be considerably less effective than possible. We made many trials of silvering small mirrors (3″ x 3″), mostly by the Brashear process, but several also by the Rochelle salts method.[3] In no case did we obtain a surface giving as high a reflecting power as those given.

[1] Reprinted by permission, from the *Journal of the Royal Astronomical Society of Canada,* Nov., 1929. The senior author is now the Director of the David Dunlap Observatory of the University of Toronto—Ed.

[2] "Methods of Silvering Mirrors" by H. D. Curtis, *A.S.P.*, Vol. 23, 1911.

[3] *Ibid.* Vol. 23, p. 17.

Columns 4 and 5 give the results of our two best mirrors when a few days old. It is quite possible that, when freshly deposited, the surface was more reflecting in the violet. Both these mirrors looked first class, giving the sun a deep blue color when viewed by transmitted light and the sky light without any tinge of yellow when viewed by reflected light. Our experience has been that a reflecting power at $\lambda 4000$ which is greater than 65 percent is difficult to obtain.

The reflecting powers of the various mirrors were measured from time to time as the silver coat tarnished and notes made of the appearance to the naked eye. No attempt was made to reburnish the silver, but it was wiped off lightly with absorbent cotton to remove any dust.

The method of measuring the reflecting power was briefly as follows. A small automobile light, 12 volt, 24 c.p., was aged and supplied with current from a storage battery, the current being held, by a resistance, constant to within $1/100$ of an ampere. Usually no adjustment of the rheostat was necessary, and the position of the needle of the ammeter stayed constant even when viewed with a magnifying glass giving 10 diameters' magnification. The current probably varied in most cases less than this amount. The light illuminated a diffusing screen about $1\frac{1}{2}''$ in diameter, so placed as to flood the collimating lens of a small spectrograph, the collimation always being carefully checked. The mirror whose reflecting power was to be measured could be introduced between the diffusing screen and the slit of the spectrograph, and alternate exposures given to a photographic plate for direct and reflected light. As many as 15 to 20 exposures could be made on one plate. The densities of the images were measured at various wave-lengths, by a wedge method, and curves drawn giving the darkening for various exposures to direct light. It was comparatively easy to find the exposure necessary with the reflector, to reproduce the same density as any given exposure to direct light. Sensitometer squares were imprinted on many of the plates for the various emulsions used, in order to determine the correction necessary to transfer these equivalent exposure times into reflecting power. The method was much more complicated than it might have been had a thermo-couple been available, but it served very well and we think the final values, which depend on the means of many exposures, should be accurate to one percent or so.

Column 6 of the table shows the measured reflecting power of mirror No. 1 after about 40 days. The mirror was kept in a drawer in the Physics Building of the University, which is adjacent to the Chemical Building. The surface tarnished quite rapidly. In another location the same ageing might not take place for a year. The age should be judged by its appearance. The following notes were made prior to making the determinations in columns 4 and 6.

When the mirror was fresh, the filament of an electric light bulb could be faintly seen through a single coat. The filament, which had a reddish tinge without the mirror, upon being interposed, looked bluish white through the mirror. Reflected skylight looked a deep blue. The sun could be seen

through two coats of the silver without any irradiation and looked distinctly blue. Direct sunlight through a single coat gave a small amount of irradiation. Before the measures in column 6 were made the mirror looked slightly yellow, and sky light, reflected and direct, could be distinguished. There were one or two little spots on the silver surface. It would have been considered in fair condition.

The result of the measures showed that the reflecting power in the violet had fallen very considerably and it led us to the conclusion that, when the silver coat begins to look a little yellow, the reflecting power in the red and yellow part of the spectrum was not much impaired, while the reflecting power at wave-length 4000 to 3900 was not over 50 percent.

Column 7 gives the measured reflecting power of a small mirror made from polished chromium steel kindly sent us by Mr. J. W. Fecker, of Pittsburgh, Pa. This mirror was in excellent condition when it reached us and looked as bright as a silver-on-glass mirror and of a rather bluish tinge. The measures showed that at wave-length 4000 it equalled our best silver mirror. At the time of writing this note, when the mirror is about 18 months old, it looks like new, while the silver mirror No. 1 is now quite black and useless. For small amateur reflecting telescopes, where the weight of a small mirror is of no consequence, polished chromium or chromium steel should prove superior and more convenient than glass.

The Amateur's Observatory

By Leo J. Scanlon
Pittsburgh, Pennsylvania

What is probably one of the best arguments in favor of an amateur observatory is contained in a letter from Alan Kirkham of Tacoma, which reads in part as follows: "The speed and ease with which some amateurs assemble their portable telescopes is amazing; the procedure is usually like

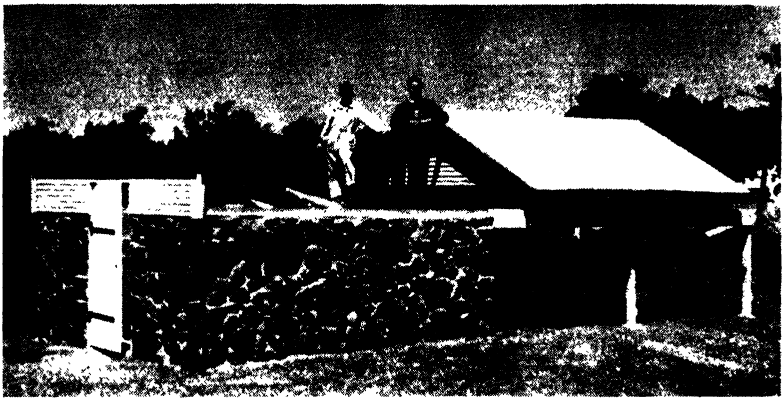


Figure 1

Las Estrellas Observatory of the Texas Observers, Forth Worth, Texas. Type A_1. Stone structure 12′ x 14′. Roll-off roof permits view of Polaris. Cost: for materials, $125; for labor, nothing (Robert Brown, chief planner, stone mason, mechanic). Described in Journal of the Royal Astronomical Society of Canada, April 1934. The Patton Observatory, also of this type (A_1), was described in Popular Astronomy, Dec. 1930.

this. First, the maker calls in half a dozen of the huskiest members of the group, and together they move the junk pile from the attic or garage to the back lot and, fortified with monkey wrenches, screw drivers and sledge hammers, the 'delikut' adjustments are completed with a speed and accuracy that leaves one breathless. By this time, however, everyone is so tired, and it's so late, that they are unable to observe, and immediately begin dismantling."

Undoubtedly you have encountered this condition in some degree in your own circle of amateur friends; but a permanently mounted instrument, protected by an observatory of whatever type, is ready for use at all times at a moment's notice; it is almost axiomatic that one cannot become fully acquainted with the whims and possibilities of a portable telescope in less than a year's service. This time could be fractionized in an observatory, and con-

FIGURE 2

The Bouton Observatory, St. Petersburg, Florida. Type A_2. Built by T. C. H. Bouton and described in Popular Astronomy, Feb. 1930. It is 14′ x 14′, with two stories (shop below). Walls are cement stucco on wood. Raised projection on one roof section overlaps other section.

FIGURE 3

An observatory built by Harold B. Webb, Jamaica, Long Island N. Y. Type A_3. Described in Popular Astronomy, March 1931. Inside dimensions 10′ x 10′.

sequently greater appreciation of the telescope would ensue and a longer useful observing life result.

Three additional reasons for building an observatory, fully as important as the foregoing, are: it protects the instrument when not in use; cuts off wind and stray light; and, last but not least, keeps the feet dry while observing, which is of great importance.

These advantages permit one to carry on worthwhile observations from a fixed location, from which the appearance of the sky quickly becomes familiar, saving much time in locating celestial objects. Under such favorable

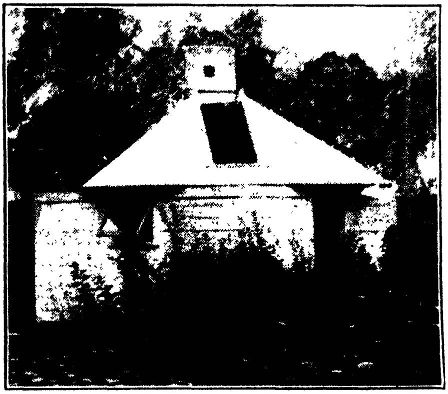


FIGURE 4

Waldo Observatory, built by J. Ernest G. Yalden, Leonia, N. J. Type B_1. Described in Popular Astronomy, May 1922.

conditions the telescope is more likely to be placed in accurate alinement and remain so, setting circles become more than theoretically desirable, thus widening the field of observation, and with a clock drive, which is a foregone conclusion in an observatory, work can be carried on with a certain amount of comfort and freedom from interruption. To complete the ideal picture, we need only set up a well figured mirror in a Springfield mounting, to have all that any amateur could desire. This mounting, with its fixed observer's position, comes into its own in an observatory.

Size of Observatory: Unless your surroundings are such as to make it an impossibility—in which case you had better look for a more favorable location—**don't build an observatory less than ten feet square.** Make it even larger if possible; anyone who has constructed an observatory of this size or smaller will be the first to advise you against cramping yourself for space. It requires no more effort to build one of proper size than to make one too small; it makes little difference, when you are on the north end of a south-bound saw, whether the plank you are cutting is ten feet, or ten miles,

long—the work is the same. The slight additional cost of materials will be more than paid for by the extra space and convenience.

Avoid building the observatory on top of an existing building, especially if the lower one is of frame construction. If it is of brick or masonry, however, it offers a good base for the observatory, but presents the problem of installing a suitable pier. If at all possible the observatory building should be separate from all others, and as far removed as conditions permit. The base of the observatory (which is that part from the ground up to

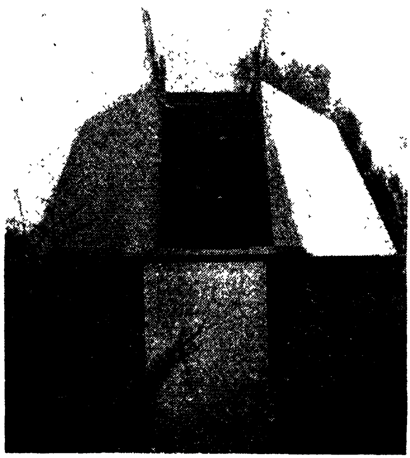


FIGURE 5

The Wright Observatory, Berkeley, Calif. Type B_2 Lift-off shutter, with hinged zenith hatch. Same dome is shown with picture of Mr. Wright, at the end of his chapter on the Schmidt telescope.

the track or rollers) should preferably be rectangular in outline; this shape is easier to construct and its corners offer ample space for desk, chairs, chart cases, etc. Climatic conditions often play an important part in determining the shape of this base; if it is likely to be piled high with snow for several months of the year, sufficient slope must be given the projecting areas, or they should be eliminated entirely, as in the case of a circular dome.

Weatherproofing: One question that arises in the mind as soon as an observatory is mentioned is, "Will it be weathertight?" This should give little trouble. After investigating this point, in connection with at least a dozen amateur observatories, only one case was found in which the builder claimed that water entered during rains. Further correspondence revealed that the shelter in question was not a permanent structure and admittedly was a makeshift.

Rollers: No matter what type of observatory is finally decided upon, use as few rollers as possible to achieve the motion desired, whether it be upon a straight or a curved track.

These rollers should be about 4″ in diameter and not more than four to six in number, for a revolving dome. A roll-off roof would require four to eight, depending upon the size and whether it was one-piece or two-piece roof. If these wheels can be secured with ball-bearing centers, so much the better. Warehouse truck wheels serve admirably for this purpose. Ball-

FIGURE 6

Left: Dome of the 24″ Clark Refractor on Mars Hill at the Lowell Observatory, Flagstaff, Arizona. From a photograph by O. S. Marshall of Springfield, Vt. and Pasadena, Calif. Esthetically the angles of side and top are pleasing. Right: Dome of the 61″ Wyeth Reflector at the Oak Ridge Station of Harvard College Observatory, near Harvard, Mass. The square base of brick surrounds a concrete cylinder, on top of which the dodecagonal turret revolves. The walls of the turret are faced with corrugated asbestos board over Celotex; the roof is of similar material, water-proofed with five-ply tar gravel roofing. The internal structural steel girders are painted with aluminum. To provide the shutter, one vertical section of the turret opens, giving access to very low altitudes, and a section of the gently sloping roof slides back—a simple arrangement.

bearing roller skate wheels have frequently been used but, due to their smaller axle diameter, more of them must be used, in order to take the weight. In a roll-off roof observatory, the part of the track which extends beyond the observatory should be well supported, to prevent sagging when the weight of the roof is on this track. The track itself should preferably be a "T" of angle iron, with the stem of the "T" vertical; in this case grooved wheels would be required. The use of this type of wheel and track eliminates the necessity of removing snow and sleet from the track in the winter.

The Sliding Roof Observatory: For a practical, inexpensive amateur observatory, one with a sliding roof has much to recommend it. In one plan, type A_1 (see table of types at end of chapter), the entire roof rolls off as a unit (Figure 1). In another (Figure 2) the roof is divided either transversely or (Figure 3) longitudinally. This point can be settled by the

builder—all are practical. This type of observatory offers an unobstructed view of the skies, permitting quick setting on objects. Since there are no shutters to operate, it is easy to open, even when heavily laden with snow.

When the sliding roof is opened, the interior of the observatory quickly adapts itself to the difference in temperature, which is a great advantage with a reflector. If it is desired, one may paint the outside of the observatory a light color (aluminum paint is best), so that the heat absorbed during the summer day will be minimized; conversely, the interior of the observatory should be painted dead black or at least a dark color, so that the absorbed

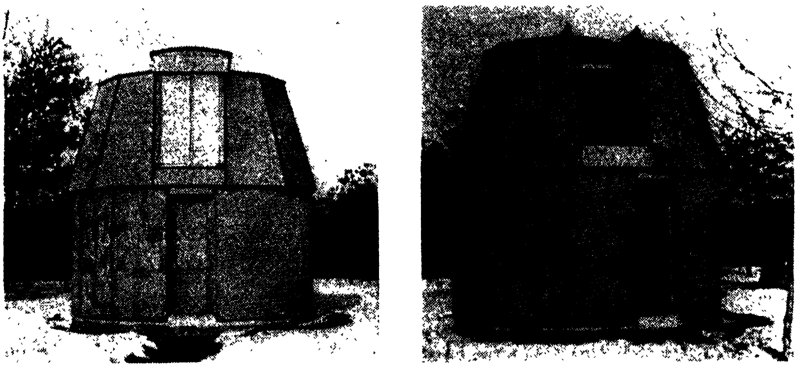


FIGURE 7

Observatory similar in type to Mars Hill, built by A. R. Leuchinger of Wantagh, N. Y. Type C_1, which the author favors as combining the advantages of the hemispherical dome with flat construction. Note simple hinged vertical shutters and sliding zenith hatch.

heat will be quickly radiated. A dark dome also reduces the glare of moonlight, and permits the eye to remain at maximum sensitivity for work at the telescope.

When the observatory is in use, one side of a split roof can remain closed, or the one-piece roof can be rolled off part way. This helps to protect the instrument and observer from sudden gusts of wind and stray light, against which this type of observatory offers but slight protection. Many well-known variable star observers, both in our own country and abroad, favor the sliding roof observatory. This indicates that an unobstructed sky is of great practical value.

Domes: While the average amateur hesitates but little before planning to build a flat, roll-off observatory, he often labors under the impression that a revolving dome is a job only for the professional mechanic. This is not really the case—but a knowledge of the use of tools helps a lot. The only difference is that, instead of working to a straight line in making the

dome or shutter or in lining up the track, you work to a curve, and must be a little more exact.

The connecting link between the roll-off roof observatory and the revolving hemispherical dome is the pyramidal or cylindrical structure. It is in these *B* and *C* types (see table of types) that we find the most practical "in-between" observatories. The simplest, easiest, and least expensive is the

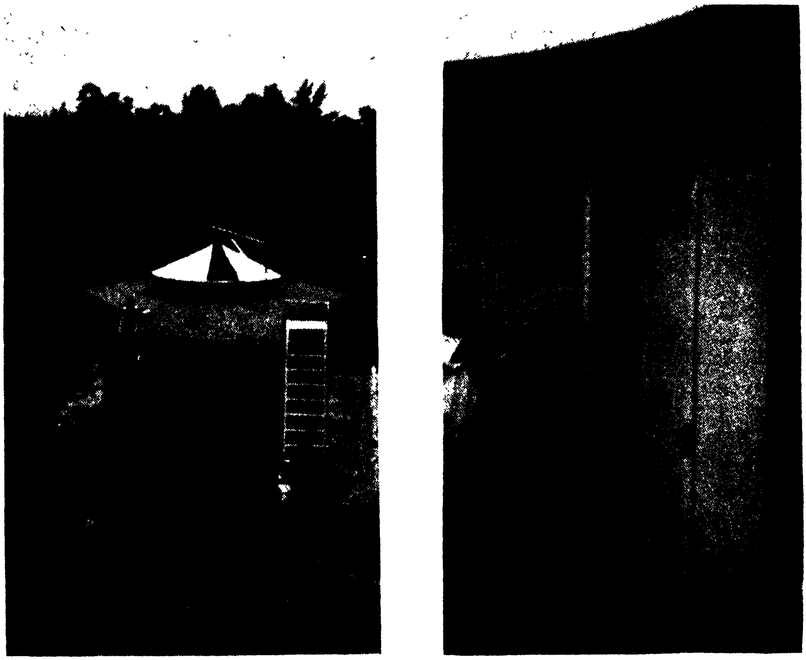


FIGURE 8

Observatory of Adrian Williamson, Monticello, Ark. Type C_2. Brick Walls. Entrance room (study and library) at front, hexagonal 16′ observing room in rear. The revolving dome is of galvanized iron and has a shutter opening with a lift-off sector for winter use. In milder weather, the entire dome may be lifted off by means of the jib and jack shown in the two pictures.

low pyramid, embodying four inclined triangles for the roof area, and a simple lift-off or hinged shutter, with or without a separate zenith shutter. The latter is well illustrated in the Yalden Observatory (Figure 4), designed many years ago and still in service. The entire roof revolves on a track and roller system, with guide and hold-down brackets to prevent lateral or vertical motion at all times. An observatory similar to this has been constructed by Woods and Watson, of Baltimore, in which the entire build-

ing, including side walls, revolves on a track system placed on the floor of the building; Croston of Tacoma went a step further and placed the track and rollers under the floor, so that the entire building revolves by motor. The latter observatory consists of an 8′ cube, the entrance door serving as part of the observing slit, while part of the cornice and a section of the roof are hinged in order to give vertical vision.

A further development of the pyramid is to increase the number of

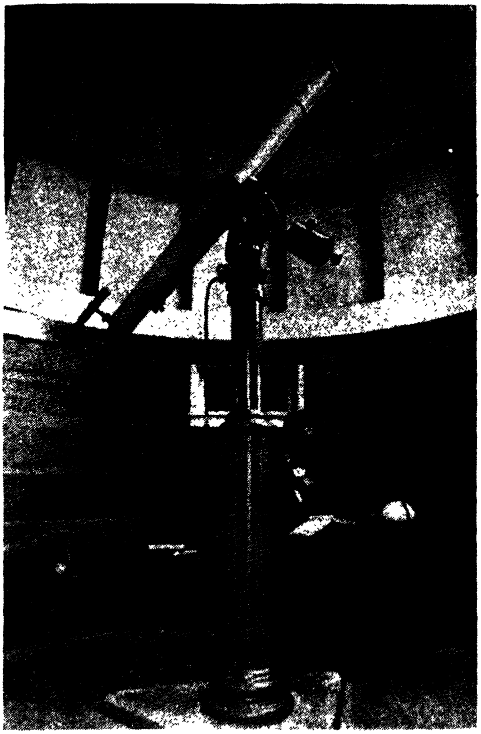


FIGURE 9

Neat interior of an Observatory built by Robert E. Millard, of Portland, Oregon. Type Wc. Note the inter-rib bracing.

sides of the dome structure, and bend the triangular areas of each side at one or more points between base and apex, giving a more pleasing structure (Figure 5). Such an observatory, by Wright, illustrates the facility with which hinged shutters can be used on this structure, which is composed

entirely of straight lines and flat planes, except for the track and roller system.

If we do not attempt to follow too closely the hemispherical idea in constructing our dome, a structure that is at once pleasing to the eye, easy to construct, and highly practical, can be secured by building more on the cylindrical side. The fact that two of the large observatories in America, the Oak Ridge Station of the Harvard College Observatory and Mars Hill

FIGURE 10

Exterior of the Millard Observatory, shown in Figure 9, attractively photographed by W. Boychuk. Diameter 10'. Height from floor to top of dome 11'6". Panels of fixed base part are of Celotex. The light canvas dome turns on twelve ball-bearing roller skate wheels, with eight similar wheels acting as thrust bearings on the inside of dome ring. Described in Popular Astronomy, May 1930.

at Flagstaff, Arizona (Figure 6), are constructed along these lines, should encourage the amateur to duplicate them. Retaining the straight-line features for ease of building, if we construct a slightly tapered cylinder, topped with a flat or sloping roof, we secure such an observatory as built by A. R. Leuchinger, of Wautagh, N. Y., (Figure 7), which carries us over into the C types. It is the writer's opinion that this is the most practical observatory between the roll-off roof type and the true dome. It is simple to construct, and has few faults. Note that Leuchinger elevated the zenith hatch

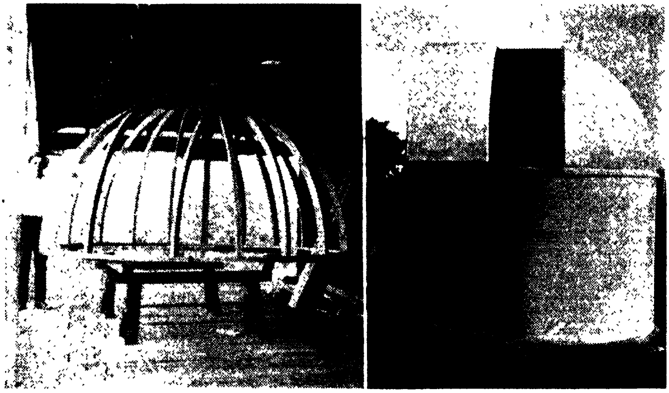


FIGURE 11

Observatory built by Fred L. Farmer, Yakima, Wash. The dome ring is made of a thickness of 1" x 4" superposed on a thickness of 1" x 3", each cut to 5' radius. Frame of the shutter is ½" angle iron, on which wooden strips are fastened to support the slats. The dome is covered with heavy canvas. The walls of the fixed base are made of Beaver Board. Cost of material (1932) $60.

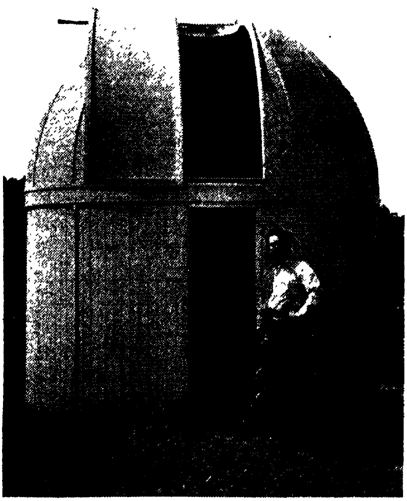


FIGURE 12

Observatory and 12" reflector of K. F. Davidson, Marshfield, Wis., type Wc. Dome is of Masonite Presdwood, and is made in spherical triangular sections bolted to wood ribs. Slot 30" wide, concrete floor 7" thick. Shutter one piece of Presdwood screwed to wooden framework, sliding in grooved oak track.

FIGURE 13

Pacific Union College Observatory, Angwin, Calif. Type Wm. Dome housing 22' diameter, 14" open fork telescope on low pier, flush with floor. In this example the conventional fixed walls have been eliminated and head room at the side wall of the dome is gained by providing a vertical skirt integral with the hemispherical movable dome. The entire building rotates on a series of roller skate trucks bolted to the circular concrete foundation below, the track being formed by the dome ring, a section of which is removable in the entrance doorway for oiling and adjusting rollers. In the basement is a workshop. A story placed below ground level will usually be cool in summer and free from vagrant drafts in winter. Some such hideout connected with an observatory provides the owner with a place he can call entirely his own, where peace and quiet may be obtained.

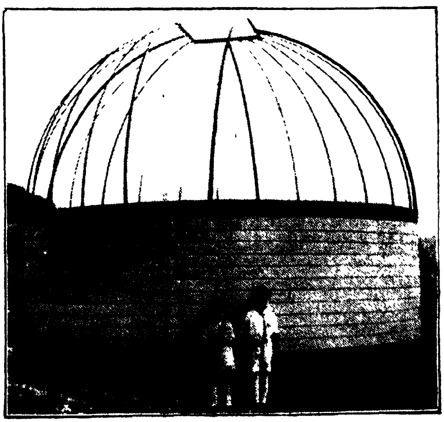


FIGURE 14

A 16' observatory by R. W. Steber, Warren Pa., Type Mc. Housing 16½" reflector. The thin ribs are arcs of ¾" angle iron (1½" around shutter opening) to which wooden slats are screwed and canvas is laid over these. Shutter consists of four hinged sections, overlapping.

track high enough above the general roof level to clear the usual depth of winter snow. The hinged shutters are easily installed and do not depend on pulleys and cable for their operation. Note the hinged board in the zenith hatch, to form a water-tight joint at the top of the shutter doors.

A further development in cylindrical observatories, more costly but not more practical, is achieved by making a short section of round cylinder and topping this with a flat or cone roof. A good example of the latter is shown in the Williamson observatory (Figure 8), in which the builder achieved not only a pleasing and practical observatory, but embodied a unique feature —winter-and-summer adaptability. Note that the entire dome structure can easily be hoisted by means of a screw jack operated from inside, and then swung clear of the observatory. Needless to say, this feature has its advantages during the summer, when it is often unpleasant to observe indoors.

The hemispherical dome that represents the least investment for the amateur, is probably one of ribbed canvas. Here all the work can be done with hammer and saw. The usual procedure in making a dome of this type is to lay out and build up two circles or rings of wood at least two ply thick, of ¾″ lumber, from 3″ to 4″ in width, and with the correct diameter to suit the finished dome. One of these rings is set stationary on the fixed base of the observatory, and is known as the base ring, while the other is used as the foundation of the revolving dome. If we attach the rollers permanently to the fixed wall of the observatory, instead of building this second ring, we can use the dome ring itself as an inverted track, and eliminate one of these circles.

The "dome ring" is used as a foundation to which ribs, and possibly guide rollers, are attached. Usually the ribs are built up two ply, of ¾″ material about 3″ wide, similar to the construction of the dome and base rings. Two main ribs are run uninterrupted across the center of the dome, and their distance apart establishes the width of the slot opening.

MAKE THE WIDTH OF THIS OPENING AT LEAST ONE-FOURTH THE DIAMETER OF THE DOME.

To these main ribs are attached the shorter remaining ribs. Inter-rib bracing is desirable, at least at one point about half way along the arc of the ribs. These braces may be light, and will serve as additional supports for the canvas (Figures 9, 10). The rollers are usually attached to the underside of the dome ring, and roll on the track, but as suggested heretofore, if we mount the rollers permanently on the fixed base of the observatory, we can eliminate one ring and cause the dome ring to act as an inverted track. If this method is used, it will be well to provide about four "guide" rollers acting against this revolving ring to prevent lateral movement of the dome.

The rib construction is clearly shown in Figure 11. Either canvas, composition board or sheet metal sections may without difficulty be fastened to the wooden ribs so formed. Davidson's dome (Figure 12) represents type *Wc*.

A fine example of wooden-ribbed dome, metal covered (type *Wm*) was

constructed under the direction of Prof. Newton, at Pacific Union College, and embodies the revolving observatory feature (Figure 13). This dome, 22′ in diameter, houses a 14″ reflector constructed by the students, under the direction of their instructor. It is mounted in an open fork, close to the floor of the observatory, and to take advantage of the full sweep of clear sky near the horizon it was found necessary to extend the slit opening downward, or else to mount the telescope on a higher pier, requiring the observer to perch atop a ladder. Extending the slit opening was considered more practical than raising the pier, and, to eliminate the necessity of installing an undersized entrance door (which has frequently been done in amateur observatories), the track and roller system was moved down to the base of the observatory walls, so that the entire building revolves. The entrance door to this observatory is directly opposite the slit, and through it objects on the

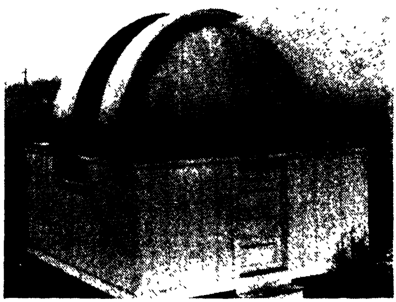


FIGURE 15

Valley View Observatory, Pittsburgh, Pa. Constructed by Leo J. and Larry Scanlon. Type Om. First of several all-aluminum self-supporting observatory domes, 12′ diameter, with weathertight reinforcing seams of great strength. Simple and effective construction requiring only hand tools and no previous experience in sheet metal work. Described in Scientific American, July 1931.

horizon are within range of the telescope. The basement of this observatory, reached through a trap door in the floor, contains a dark room and workshop. Gangs of ball-bearing roller skate wheels mounted on small tracks are placed at frequent intervals around the foundation of the observatory, the track being attached to the dome and revolving with it. The wheel trucks are so mounted that they can be adjusted individually for height.

If, instead of wooden ribs, we are able to substitute arcs of flat or angle iron, to which the canvas, wood or sheet metal is attached, we may get a more substantial job, but one which is a little more difficult to construct (Figure 14). Similar construction, but on a more elaborate scale, was employed in a 12′ observatory in Morrisville, Vermont (Figure 19). In this case, "T" ribs of steel were rolled with the vertical web outward, flooring boards were used to fill in the space between, and the whole was sheathed

with copper. The cost of this observatory was well over $1000, the fixed walls being of brick construction.

Why not entirely eliminate these cumbersome, expensive ribs? A practical way to accomplish this is to use a material which will be self-supporting. Sheet metal is probably the only material that answers this purpose; one of the early examples of a sheet metal dome was described by Bell, in "The Telescope," but since the construction required professional assistance, is

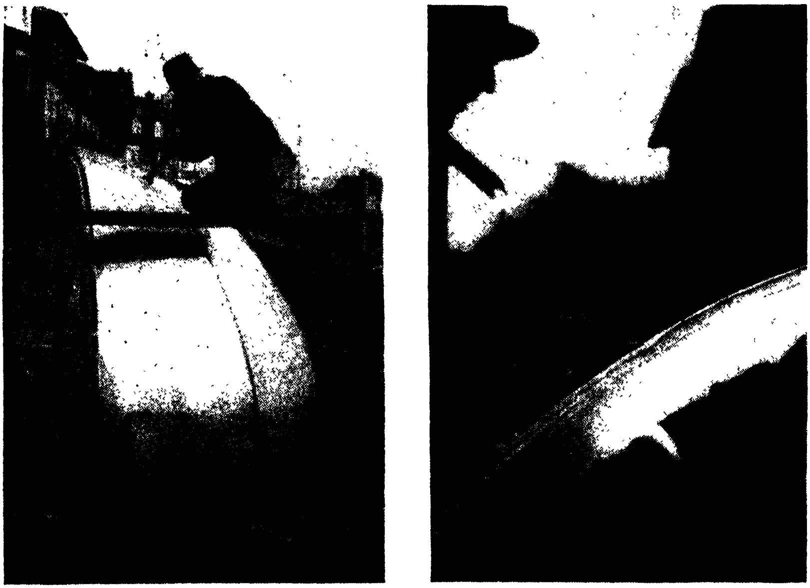
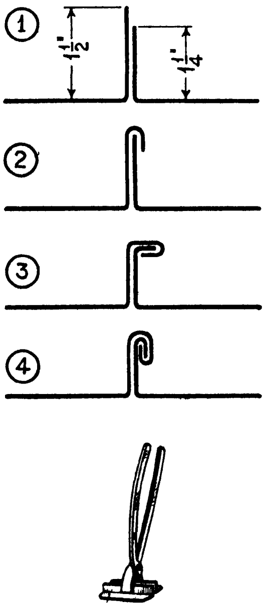


FIGURE 16

Left: How the gores of the dome at Valley View Observatory were joined—making the double-turned standing seam. Right: After the right-angle bend (stage 3, Figure 17, left) is bent with the tongs it is finished with a mallet backed by an iron dolly.

not entirely suited to amateurs. Later examples of sheet metal, self-supporting domes indicate that others have preferred to dispense with these ribs. Dr. Camilli of Pittsfield, Mass. (*Scientific American,* March 1934), riveted and soldered the gores of his observatory together, requiring about 50 pounds of solder, 3,000 rivets, and considerable labor, to achieve this end. David Brown of Pittsburgh completed a 14′ dome having 36 gores of sheet metal, bolted and riveted together, forming a very substantial, smooth-appearing dome. A slight lap was required for each sheet, and the joints were painted with a waterproofing material after fastening.

Both of these methods of joining the sheets of metal, and several others, were considered before building the Valley View Observatory (Figure 15), but both were discarded in favor of a method which would require no solder, bolts, or rivets, yet which, when completed, would be more rigid than either. Since such a saving of time and money could be effected, it was thought desirable to invest the money thus saved in a better material



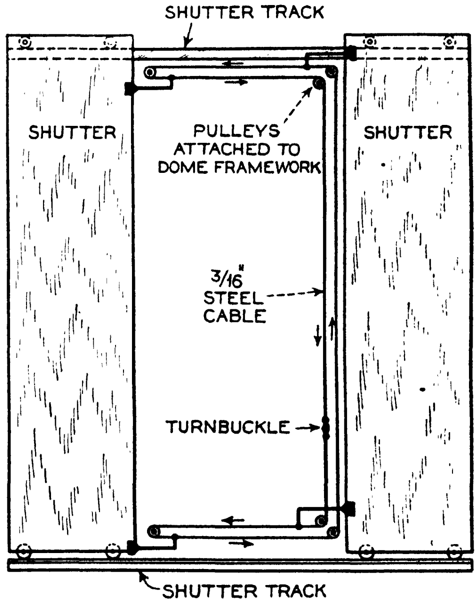


FIGURE 17

Left: Four stages in joining the gores of the seam, also the turning tool for bending the metal, improvised from pieces of one-inch angle iron and blacksmith's tongs welded together. Right: Diagram of arrangement by David L. Brown, Laurel Gardens, Pittsburgh, Pa., for opening and closing shutters on his observatory, adopted at Valley View. A cable of heavy picture wire is guided around the shutter opening by rollers (2" in diameter at right-angle turns) and made continuous by a turnbuckle. Shutters are attached at points indicated, by metal arms which are so formed as to pass each other when moving. Shutters can be opened manually by a pull on the cable, or by motor if the wire is passed around a drum at some point.

for the dome itself. Accordingly, 20-gage, half-hard aluminum sheet was chosen because of its light weight, rigidity, and resistance to corrosion. A 12′ hemisphere was constructed (*Scientific American*, July 1931) by interlocking 12 sections, each 3′ across at the base of the triangle and approximately 9′ long. The joint between the sheets is technically known as a "double-turned standing seam" (Figures 16, 17), and gives the same effect

as an external rib of aluminum, five ply in cross-section. This stiffens the entire structure to such an extent that the completed dome easily supports the weight of two men without perceptible distortion. Plans for this observatory have been lent to amateurs in several states. These domes weigh less than 250 pounds. The cost of the complete observatory at Valley View, exclusive of amateur labor used throughout its construction, was $250 (1930).

Shutters: The problem of moving the shutter on a dome is basically no different from opening a roll-off observatory—in fact, since the shutter is lighter and its travel shorter, this is really a simpler job.

In general, the problem can be solved in a number of ways. A shutter that slides laterally in a grooved track is shown in Figure 12. The builder declared that an improvement would have consisted of providing grooved

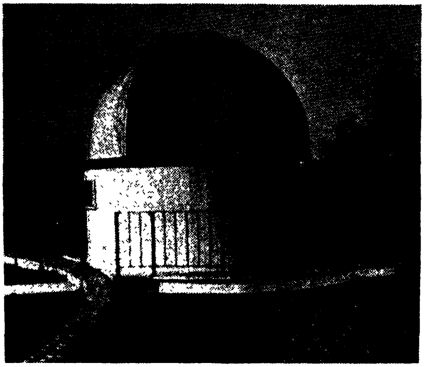


FIGURE 18

An observatory 12′ in diameter, built by H. B. Ross, Benton Harbor, Mich., to house a 12″ reflector. Type Mm. The observatory is at the edge of an 85′ bluff above Lake Michigan, and one side stands on steel columns. Shutter slides over the top of dome.

wheels (like sash-weight pulleys) running along a narrow iron track or rod, in order to prevent the accumulation of sleet which forms in the present wooden track. This dome is constructed of semi-flexible building board, nailed to wooden ribs, the joints being covered with additional strips. The shutter is made of the same material. All was given three coats of white lead, and has been found satisfactory after some years of use.

Probably the simplest practical method of making a shutter is to use a single sheet of building board, metal, or even a curved framework covered with canvas, made to fit over the arcs around the slot opening and sliding, flexed, on these arcs across the top of the dome and down over the back of it, out of the way—like the sliding part of a roll-top desk (Figure 18). Snow accumulating on the top of the dome in heavy weather probably will offer

some resistance to opening this type of shutter. The same type obscures the zenith, unless it is made in two parts or short arcs which telescope into each other, with complicated construction.

If the shutter is made to move laterally, it is possible to make the opening and shutter extend past the zenith, so that full advantage can be taken of this freedom from obstruction in photographing an object in that most favorable location.

If the shutter is so large that it is desired to distribute its weight on the open dome, it may be divided meridianally, and the same arrangement of rollers and track applied to each half. A single rope-and-pulley arrangement

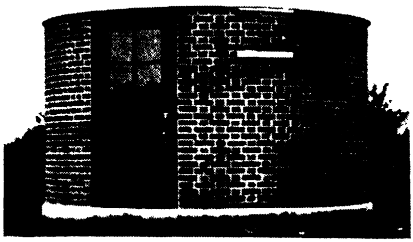


FIGURE 19

Grout Observatory, 12′ diameter, Morrisville, Vt. Type Mw. Brick walls, concrete floor, steel-ribbed dome covered with wood sheathing and copper flashing. Dome revolved by hand rack-and-pinion.

serves to open both halves simultaneously. This plan was adopted in the two Pittsburgh amateur domes (Figure 17, right).

No matter what pattern of shutter you select for your observatory **make the width of the opening about one-fourth of the diameter of the dome itself.**

Revolving the Dome: While it is usually a simple and easy matter to revolve an amateur observatory dome by grasping one of a number of convenient handles and giving a pull, various methods have been devised to do this work by motor (Figure 20).

If, instead of attaching our dome rollers to the upper or revolving ring of the pair mentioned in a previous paragraph, we attach the rollers permanently to the fixed base of the observatory itself, we can at once eliminate one entire laminated ring and provide a suitable arrangement for revolving the dome by motor. The only requirement is that we gear down a motor

(such as a second-hand washing machine motor) and, by using a friction pulley pressing against the revolving ring—preferably downward against and directly over one of the dome rollers—we can revolve the dome at any desired rate, depending upon the speed reduction used. A reversing switch may be attached to the motor, thus permitting rotation of the dome in either direction. Motors can be procured with these reversing features built in. With a 10′ dome an 1800 r.p.m. motor would require about a 30-to-1 reduction, in order to cause the dome to rotate in approximately one

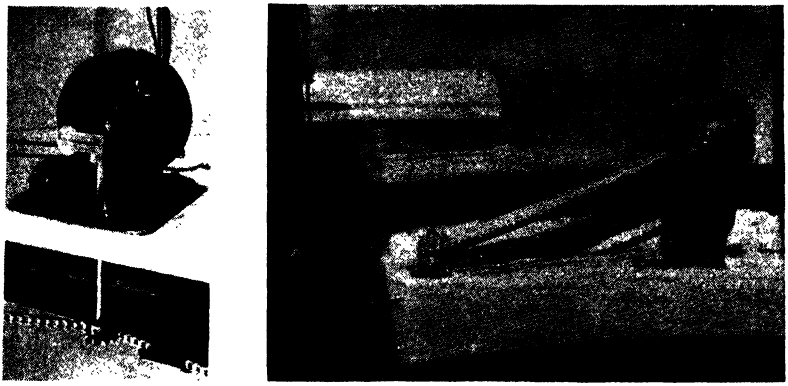


FIGURE 20

Left: Self-explanatory method for turning a dome, used by Harry Footer, of Cumberland, Md., in his 12′ aluminum observatory. The sprocket chain completely encircles the dome, and pulls against 12 hook-shaped brackets as shown. ¼ h.p. motor, 1725 r.p.m., speed reduced 20:1. Right: Friction drives on Laurel Garden Observatory Dome, Pittsburgh, Pa., built by David L. Brown. Reversible motor, ⅙ h.p., reduced 20:1 by worm gear, drives the rubber-faced truck wheel running on the upper side of the track through a 2:1 sprocket gear reduction, causing one revolution of the dome in 35 seconds. Tension on friction drive is adjustable—note tension spring and nut. Motor controlled from pier of 10″ Springfield type telescope.

minute—which is fast enough for all purposes. The motor may be controlled, of course, from the pier of the telescope, and during photographic exposures this is a great convenience, since the observer, probably following his guide star through the telescope eyepiece, can move the dome as required without leaving position.

To sum up, if you wish your observatory to look professional and indicate by its appearance the purpose for which it was built; if you wish to satisfy your own artistic desires and live up to the expectations of your friends; or if you wish to engage extensively in a photographic program—by all means build a real dome.

If, on the other hand, you are located remote from the interference of

lights, and wish to construct an observatory that will consume a minimum of labor and be least expensive; if the appearance is of secondary consideration; or if you are going to engage in the observation of meteors or variable stars—by all means build a sliding roof observatory.

TABLE OF TYPES OF OBSERVATORIES AND DOMES

Classified according to difficulty and cost of construction.

Straight-Line Observatories

Type *A*: Includes all flat or low-angle sloping one- or two-piece roof, which rolls or slides aside, or is hinged.
- *A*1: Rectangular base, one-piece, roll-off roof on tracks.
- *A*2: " " , two-piece transverse division, roll-off roof.
- *A*3: " " , " " longitudinal " " " "

Type *B*: Includes all flat pyramids with lift-off, roll, slide, or hinged shutters. (Roofs revolve.)
- *B*1: Pyramidal roof, each section in one plane.
- *B*2: " " " " " two planes.
- *B*3: " " " " " three or more planes.

Type *C*: (All cylindrical observatories with flat or slope top)
- *C*1: Cylindrical polygons, flat or sloping roof.
- *C*2: True cylinders, flat or conical roof.

Hemispherical Domes

Classified according to rib construction, covering, and total cost.

Rib designations: *W* – Wood. *O* – none. *M* – Metal.

Cover " $\left\{\begin{array}{l}\text{c – Canvas or composition board}\\ \text{w – wood}\\ \text{m – metal}\end{array}\right.$

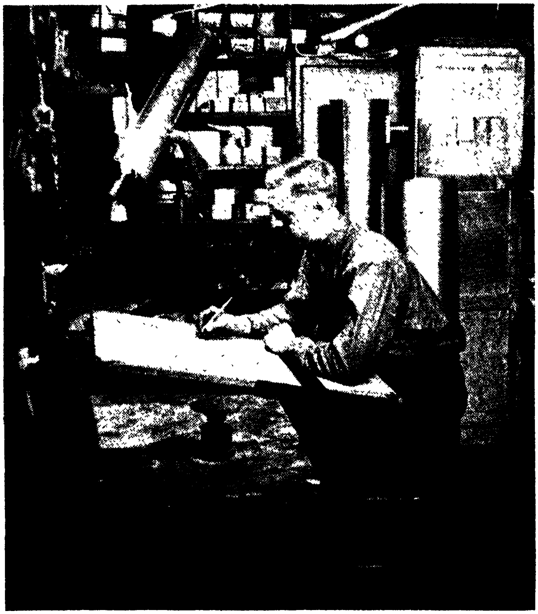
Type *W*c – Wood ribbed dome, canvas covering (or compo board).
- *W*m – Wood ribbed dome, metal covering.
- *W*w – Wood ribbed dome, wood sheathing and shingles.
- *M*c – Metal ribs, canvas covered.
- *O*m – No ribs, metal covering.
- *M*m – Metal ribs, metallic covering.
- *M*w – Metal ribs, wood sheathing, metallic flashing.

Shutter Construction for Hemispherical Domes

Classified according to simplicity and least cost.

One piece canvas flap; tied down, roll down.
Single wood framework, canvas covered; lift off, slide vertically or horizontally, roll aside, or over the top.

Single wood framework, composition board, moved as above.
Single wood framework, metallic cover, moved as above.
Single metallic framework, metallic cover, moved as above.
Double metallic framework, metallic cover, moved as above.



The author in the basement workshop of his Valley View observatory at Pittsburgh.

A Bilateral Slit Mechanism *

By R. BOWLING BARNES and R. ROBERT BRATTAIN, Palmer Physical Laboratory, Princeton University

In setting up practically any kind of optical instrument, the question of securing a good slit is one of the first encountered. Usually this slit must be constructed so that it is bilateral; so that its exact width may be read off from a convenient scale; and so that its jaws close perfectly and move accurately parallel to each other.

It is the purpose of this paper to describe in detail a slit mechanism which

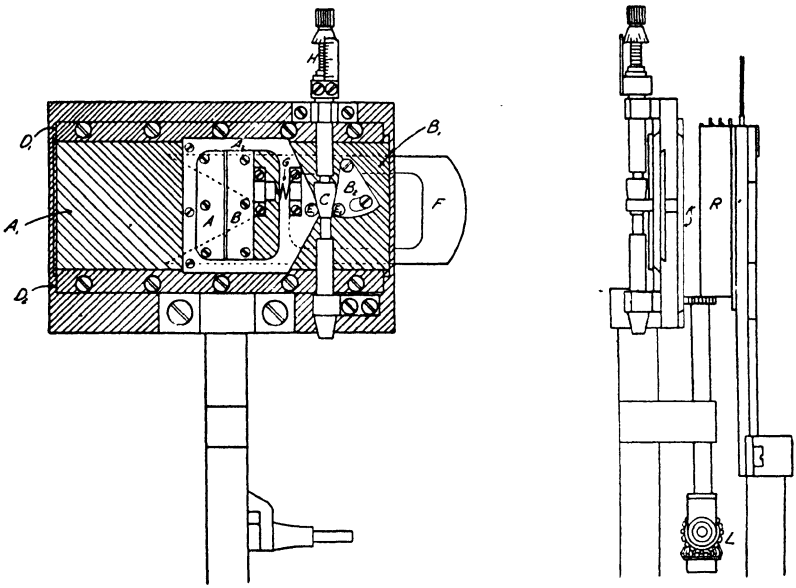


FIGURE 1

may be constructed easily and which satisfies these requirements. Because of the extreme simplicity of this design, the authors thought that it had probably been used before; however, an examination of the literature failed to reveal any previous use of this principle in a slit mechanism. The details of the mechanism are shown in Figure 1. A thrust, caused by the rotation of the screw *H*, forces the cone *C* downward (without rotating it) between the two steel pins E_1 and E_2, thus forcing the slit jaws *A* and *B* apart. The strong spring *G* holds the steel pins E_1 and E_2 firmly against the cone *C*, and the swinging plate B_2 can be set so that *C* makes contact with both

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E_1 and E_2 simultaneously. The height of the slit may be varied by means of the fishtail slide F.

Curves on the performance of a slit of this design are given in Figure 2. The readings, from which these curves were plotted, were taken on a comparator of such accuracy that the error in any of the values is not more than $\pm$ 0.001 mm. Each figure given is an average of at least five readings. Observations of the same accuracy failed to detect any deviation of the slit jaws from perfectly parallel motion. Curve (a) in Figure 2 is the calibration curve of the slit. From curve (b) it is seen that the slit is accurately bilateral for slit widths between 0.10 and 2.6 mm. but that it fails to be bilateral for smaller slit widths. This failure is due to the frame A_2 springing slightly downward when a thrust is first applied to the cone C,

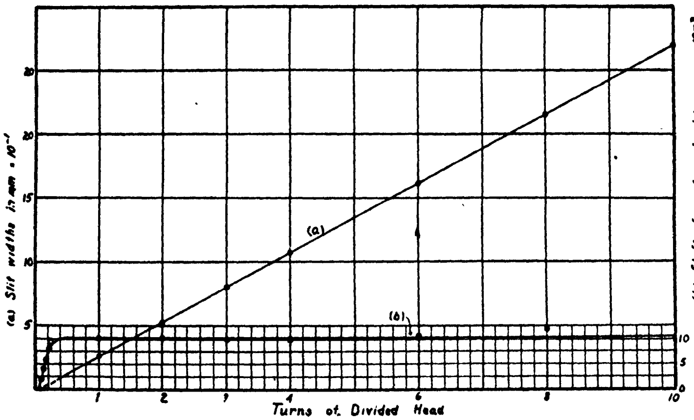


FIGURE 2

Curves showing the performance of the slit. (a) turns of the screw H as abscissae, plotted against actual slit widths as ordinates. (b) turns of the screw H as abscissae plotted against the shift of the middle of the slit as ordinates.

thus causing an unsymmetrical motion of the slit jaws. As soon as the frame has sprung as far as it can, the tension of the spring holds it in this position, and from then on the motion is truly bilateral, and upon closing the slit it comes to its original zero. Although this defect was not anticipated in the original construction, it could be corrected easily by making A_2 more rigid. If this were done, judging from the performance of the slit between 0.10 and 2.6 mm, the slit would also be strictly bilateral for widths in the range 0 to 0.1 mm and the calibration curve (a) would go linearly through zero. Other precautions which should be observed in the construction of such a slit are: (1) That the axis of the screw ensemble H be accurately perpendicular to the slit ways D_1 and D_2; (2) that the axis of revolution of the cone

C be identical with the axis of H; and (3) that the length of the slides A_1 and B_1, to which the slit jaws are fastened, should be at least 1½ times the height of the slit opening.

The slit as shown in Figure 1 was built for use in an infrared spectrometer of the type recently described in this journal by one of the authors, hence it was made with a maximum width of 3.0 mm and a height of 50 mm. The pitch of the screw H and the slope of the cone C were matched so that one revolution of H would open the slit 0.25 mm. By a proper matching of these two units practically any desired sensitivity of adjustment may be obtained. This design of slit may be built in any form or size and as rugged or as delicate as needed. Slits of this design have just been completed having a maximum width of 1.5 mm and a maximum height of 10 mm. In these slits the frame A_2 is relatively much stronger than in the original slit; and measurements analogous to the ones from which Figure 2 was plotted show a shift of the center of the slit of less than 0.001 mm. This result verifies the prediction made above that the shift in the center of the original slit would be eliminated by making A_2 heavier. As an added convenience for infrared work the slotted filter slide K, controlled by rotations of the gears L, and the filter and shutter rack R were added.

This mechanism was designed and constructed with the help of Mr. W. C. Duryea and Mr. C. R. Stryker. For their generous and skilful assistance the authors wish to express their gratitude.

Shorts

Streak of Rouge Test for Contact in Fine Grinding: "Use rouge instead of a pencil, on the tool only. Rub the mirror at right angles to the line of rouge, which should be applied very thinly with the finger tip. Examine the mirror for red stain. Put no pressure on the mirror in testing for contact —its own weight is sufficient. Pressure often results in serious scratches."—*Cyril G. Wates, Edmonton, Alberta.*

Water Drop Test for Contact in Fine Grinding: Kirkham's idea. Suppose the head of a pencil is dipped into water and the adherent drop transferred to the mirror. The volume of this hemisphere is approximately $\frac{1}{2} \times \frac{4}{3}\pi r^2 =$ .003 cu. inch, assuming ¼″ diameter of the drop. For an 8″ mirror, with approximate area 48 square inches, $.003'' \div 50 = .00006''$. This gives some idea, at least, of the thickness of the water film, assuming that it covers the entire area of tool and mirror and has uniform thickness—which it probably would not have in the average case. But the order of size of thickness indicated may be about .0001″, which is considerably finer than we can measure by the insertion of scraps of tissue paper. How much of the water goes into the pits is another factor. Doubtlessly, instead of trying to cut the calculation too fine, the better way is to make the test on a few surfaces and empirically derive an idea of its degree of precision—that is, by later observation of the figure of the mirror after polishing has been started.

Some think that the scratches which are sometimes the result of the lead pencil test described in "A.T.M." are from grit in the graphite. Others believe some sort of molecular cohesion between the surfaces pulls out pieces of the glass.—*Ed.*

Mirror Sticks to Tool: "When one is fine-grinding a mirror on a glass tool, and the amount of abrasive is reduced to a minimum, the tool and mirror will sometimes seize and stick to one another as tight as the proverbial 'tail in a mule.' This is most disconcerting, especially since it happens suddenly and without warning.

"Do not attempt to wedge them apart—the results may prove to be disastrous. Rather, submerge tool and mirror, (everything, in fact except the barrel) in a basin of cold water, the water to cover the joint well between tool and mirror. Then heat slowly until you cannot bear your hand in it. Keep water hot for a couple of hours or so, and then set it aside to cool over night. In the morning the water will have been drawn in between the two surfaces and they will separate easily. Of course, the pitch that fastens the tool to the block and the mirror to the handle will need attention, but then, what of that? This method has worked 100 percent for the writer." —*Rev. J. G. Crawford, Saunderstown, R. I.*

"When my mirror froze to the tool during fine grinding I took the contrary disks out in the back yard and played a fairly strong jet of water from a garden hose on the edge of the glass at the line of contact, and after a little while had the satisfaction of seeing the water creep in

between the two until I was able to lift off the mirror without any resistance whatever. It would be well to be careful about the temperature of the water."—*Dr. John W. Straight, Santa Ana, California.*

"If the two disks are not quite coincident, but slightly overlapping—as usually happens—I have placed them between the wooden jaws of a large cabinet maker's hand screw (Figure 1) and left them for a time. Generally they were found to have come apart."—*R. W. Porter, Pasadena, California.*

"When my two disks stuck together I wiped the surplus water off the edge and applied alcohol. The alcohol penetrates between the disks and heats a little as it mixes with the water."—*W. B. Hiner, San Jose, California.*

"Your suggestion, also those made to me by the Alvan Clark Co., and the American Telescope Co., failed to separate the two disks which I reported to you a year ago as being stuck together. I present a statement of my efforts to separate the two, which became stuck together while grinding with No. 600 Carborundum:

July	9	—	Placed them in warm water	10 minutes
"	10	—	Placed them in turpentine	10 minutes
"	15	—	In carbon tetrachloride	23 hours
"	18	—	Denatured alcohol	96 hours
"	24	—	In hot water	15 minutes
"	24	—	On ice	24 hours
"	25	—	In ice water	24 hours
"	26	—	In hot water	15 minutes
"	27	—	Carbon tetrachloride	72 hours
Total useless effort				240 hours

Then I placed the two disks on edge on the work bench and, using a Durham safety razor blade and a piece of two-by-four, separated them in 10 seconds.—*R. A. Bell, Cleveland, Ohio.*

"Stand midway between the rails on a convenient railroad, holding the two stuck disks exactly opposite the pit of the stomach (precision is important here) and wait till something arrives. This has separated the disks in most attempts, but if it fails the first time try again."—*Casey Jones, at the round-house.*

Warping of Wood on which Tool is Mounted à-la-Ellison: "Saturating the wood with hot paraffin, in order to obviate trouble from warping when water enters its grain, is not entirely successful, due to difficulty of covering and sealing every pore in the wood. Binding and sticking of the mirror to the lap during polishing may often be traced to warping of the tool block. Shellac and paraffin help exclude moisture, but it is very difficult to seal every crack and joint, and moisture seeps in, destroying the figure of the mirror by flexure. Cement an iron or aluminum plate to the wooden block, and then cement the tool to the metal plate, using soft pitch of the consistency of chewing gum at mouth temperature. The soft pitch will hold the plate and tool securely, but will yield under stress of warping, permitting the tool to

retain its shape. The metal plate resists flexure and prevents distortion of the tool and mirror. The writer uses a $\frac{1}{2}''$ cast iron plate of suitable diameter. An ordinary stove-lid may be adapted in emergency. Metal plates may be readily cleaned of adhering pitch by playing the flame of a torch or bunsen burner over the surface and then wiping off the melted pitch with an old rag. Even when using the iron plate between the block and the tool, it is well to paraffin the block nevertheless, to prevent the warping as much as possible. Also, it is best to use a very dense, hard wood such as birch (or teak, if the latter can be procured). Pine wood is utterly unsuitable; nor is oak, on account of its porosity, very much better. Time spent in properly preparing the support for the tool so that it will not be flexured will eliminate much trouble and exasperation."—*S. H. Sheib, Richmond, Virginia.*

Commenting on this, A. W. Everest writes: "There is a whole lot in

FIGURE 1
Porter's method of unsticking stuck disks.

this, if you are using thin tools like those supplied with the kits. I am a stickler for tools of the same thickness as the mirror. This overcomes most of the trouble with amateur sizes. I support the tool directly on the bench, with three generous gobs of pitch, or a ring just inside the edge, and don't seem to have any trouble from tool warpage."

Test for Complete Polish: "We note that not more than five percent of mirrors sent to us for silvering are fully polished. The following test, used by us on our own work, might be a revelation to many.

"Take a small reading glass or other simple lens and, using it as a burning glass, throw a bright spot upon the supposed polished surface. Either an electric light or the sun may be used, though the latter is much the better. A surface which seems quite fair using a magnifying glass in the usual manner will now appear as a gravel bed even to the naked eye. If the test seems too drastic, try it out on a professionally polished surface, such as a B. and L. prism. If the prism surface is clean and free from grease, even the most intense 'burning glass' spot can scarcely be detected by front face reflection." —*Tinsley Laboratories.*

A method of detecting the most minute pits and scratches: "Place a lamp

at the right of center of curvature, where the pinhole normally goes in the knife-edge test. Then place the eye where the knife-edge would go. Move the head so that just the edge of the cone of reflected rays is seen."—J. H. Hindle.

"I have found when looking for small pits or scratches without the aid of a lens, that these are more easily seen if one looks through the glass from the back. I have found fine scratches from the back that I have never been able to detect from the front until they showed up in the polishing process. Apparently light is more readily caught by a pit or scratch and sent into the glass than reflected out of the pit. If I am not mistaken this is the reason why the inside frosted light bulbs allow more light to pass out than did the old outside frosted ones."—*John Tom Hurt, Rice Institute, Houston, Texas.*

Reversing Knife-edge: If the knife-edge is made to cut the cone of rays from the direction opposite the normal—for example, with the pinhole on right and the knife-edge to left of it but moving into the rays from the right to left—the normal shadows will be reversed, those of a paraboloid becoming those of an oblate spheroid. This method is helpful in more closely finding the "crest of the doughnut," etc. A special knife-edge made like a broad slit, will permit quick change from normal to reverse direction and back.—*Ed.*

Precision in Reading Knife-edge Shadows: "Very few persons find it possible to read Foucault shadows to closer than $1/100''$, and indeed it requires considerable skill and practice to read accurately to $1/50''$. Claims made by those who profess to read more closely are generally based upon fallacy. However, it is possible with patience and care to obtain results of considerably greater exactness.

"In reading photometers, colorimeters and similar instruments, the fields of which present the same gradual and uncertain transitions from light to shade that we observe in the Foucault test, it is recommended to make many readings, throwing the instrument well off the end point after each reading, and making the next reading by approaching from the opposite side. Thus in the Foucault test, if one reading is made by approaching the focal point from within focus the next should be made by approach from without focus. After obtaining eight or ten readings in this manner, the results are averaged, and any individual readings which depart widely from the average are rejected, after which the average is taken of the remaining results. After resting the eye, and then making a similar set of observations, it will be found that the averages of the two series agree very closely.

"The procedure consumes considerable time, and it is very necessary to rest the eye at intervals, but the greater precision obtained in this way is worth the extra effort. The method is unnecessarily exact for any except the very last stages of figuring, or in checking the figure of a completed mirror, where the utmost precision is desired. It is particularly to be recommended in making zonal tests, especially on mirrors of short focus, where the central shadows are deep and indefinite.

"The observer is fully justified in rejecting any 'wild' results which ob-

viously depart too far from the averages. If one obtains eight or ten readings that are fairly close together, errors in one direction will be at least partially balance errors in the opposite direction, and the average will be very close to the truth. For greatest accuracy, several series of readings should be taken, and the average of all the series used as the final result.

"To satisfy one's self of the degree of precision of which the method is capable it is recommended that, after having measured a mirror as outlined, it be re-checked after the lapse of a sufficient period to remove any lingering recollections of earlier readings which might insensibly bias the observer. Still better it would be to have the mirror checked by a disinterested person. If the mirror is tested in zones, the use of a second mask, exposing zones of different radii from those of the first mask, is recommended, particularly if the results are plotted on cross-section paper. The results obtained by both masks should fall along the same curve."—*S. H. Sheib, Richmond, Virginia.*

The Inside-and-outside Test: "Some years ago while making zonal measurements on a 6″ mirror, which, under the Foucault knife-edge test, had all the characteristics of a correctly parabolized mirror, a zone was found about 1¼″ in from the outer edge that was slightly higher than the rest of the curve. With the pinhole on the right and knife-edge on the left, the high zone happened to be so placed that its shadow was thrown to the left edge of the mirror, and was consequently lost in the crescent-shaped shadow normally characteristic of a parabolic surface of revolution.

"Previous to the zonal measurements, described above, the mirror was checked for turned edge with the eyepiece test. The outer edge of the expanded disk, seen with the eyepiece inside of radius of curvature, appeared as it should, with the central area uniformly bright and the outer edge shading delicately into the grey. On close inspection, however, a ring, just a bit darker than the adjacent area of the image, was noticed immediately inside and concentric with the shaded area on the outer edge. This darker ring corresponded exactly with the high zone found in the zonal measurements. Drawing the eyepiece outside of R. of C., the ring which appeared darker inside of R. C. reversed and appeared brighter than the adjacent area.

"Other mirrors on hand at the moment, which were in various stages of figuring, were scrutinized and in each case it was found that high areas appeared dark and low areas appeared bright inside of R. C. and conversely, outside of R. C., dark areas denoted low spots and bright areas were indicative of high spots.

"Applying a bit of reasoning it was readily seen why this should be so. With a perfectly spherical mirror, rays of light from a divergent source placed at the radius of curvature, are reflected to form an image at the source, and the expanded image seen with an eyepiece inside of R.C. is uniformly illuminated. Any departure from a perfectly spherical surface changes the radius of curvature of the area affected, causing the reflected rays to come to a focus slightly ahead or back of R. C. Consequently, in

viewing the expanded image inside of R. C. of a mirror having a high zone, its light at the eyepiece will not be quite as close to focus, and therefore will be slightly more diffused than the light reflected from the remainder of the surface and is slightly darker than the rest of the image. Outside of R. C., the converse is true, *i.e.*, the high area, having the longer radius of curvature, the reflected light passes through focus slightly farther back of R. C. and, being less diffused than the light in the main beam, would therefore appear brighter. The same reasoning may be applied in the case of a low zone, except that the reverse is true. A low zone, having a shorter radius of curvature than the rest of the surface, its reflected light comes to a focus ahead of the main beam, is therefore less diffused and appears

FIGURE 2

Jean Bernard Leon Foucault (1819–1868).

brighter in the expanded image inside of R.C. Outside of R.C., it is more diffused and appears darker.

"This simple but very effective test has been found to be a great time saver in testing and figuring the hundred odd mirrors which have passed through the writer's hands; in fact, with experience, one can very accurately judge the correction applied to a mirror after a few moments' study of the expanded image inside of focus. Beginners have found it exceptionally valuable in helping them interpret the Foucault shadows."—*L. E. Armfield, Milwaukee, Wisconsin, in* Amateur Astronomy, *Sept. 1935.*

[EDITOR'S NOTE: The germ of the above test was briefly described by Leon Foucault, in his celebrated "Mémoire sur la Construction des Télescopes en

Verre Argenté," published in Vol. V of the Annals of the Observatory of Paris, 1859. Mr. Armfield developed it independently and considerably further than Foucault. It is interesting to note in the same memoir, that Foucault similarly described the germ of the Ronchi test; in other respects he was far ahead of his time. He was a physicist and combined with this a flair for inventing apparatus for his experiments—a practical man, no

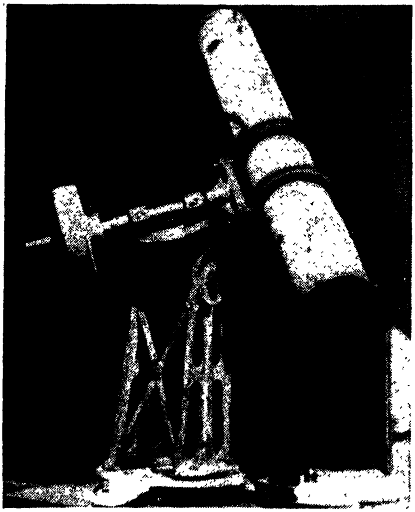


FIGURE 3

Left: An old mounting by the late famous professional, Brashear. Note how the declination axis is attached to the tube—by a heavy plate with integral ribs, the whole acting as broadly spreading stress members, much as a sturdy tree is solidly rooted to the earth by means of buttress-like members where it enters the ground. Right: Mounting of a 6″ made by Lincoln K. Davis of Brockton, Massachusetts. This mounting also has a stiffened plate to carry the stresses from the declination axis to the tube.

arm-chair theorist. His picture (Figure 2) deserves to hang in every amateur's workshop—chief patron saint of the telescope making hobby.

Note how lucidly Foucault described his great test, in the memoir named above—the first account of the then new test. "We place a point of light in the vicinity of the center of curvature, in such a way as not to obstruct the returning rays; after crossing one another these rays form a divergent cone in which the eye is placed and moved up toward the focus until the surface of the mirror appears entirely illuminated; then, with the aid of a vertical screen, we intercept the image to the point at which it disappears entirely. This maneuver produces for the observing eye a progressive ex-

tinction of the brilliance of the mirror which, in the case of exact sphericity, remains until the last moment and with a uniform intensity over the entire surface. In the contrary case, the extinction does not take place simultaneously at all points, and some contrast of lights and shadows gives the observer, with an impression of exaggerated relief, the perception in black

FIGURE 4

The Everest "Town Pump" mounting. The cross of the "T" is full sized and rigidly carries the strength of the heavy declination axis clear through to the tube and well out on it.

and white of the prominences and depressions which mar the spherical figure."

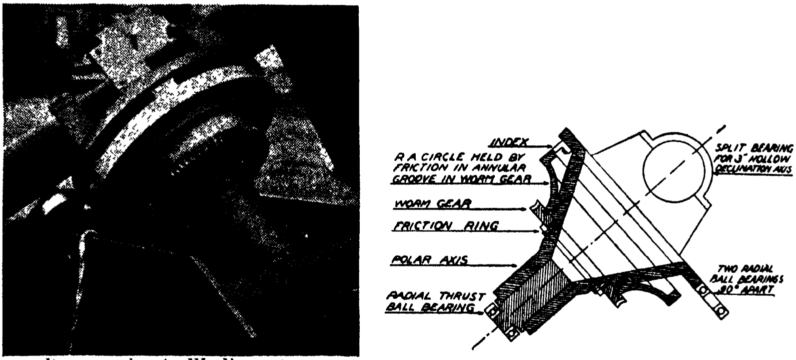
Many writers have described the same phenomena, but few so clearly as this.

The germ of the Ronchi test is suggested in the following, by Foucault: "If we wish to inspect the mirror as a whole, by a blow of the eye, it is necessary to take for the object a piece of square-meshed netting whose image becomes very sensitive to deformations at whatever part they display themselves. Suppose, as often happens, the mirror, exactly spherical in its central portions, is opened out toward its edges by a progressive lengthening of radius of curvature . . . such a mirror will give an image in which all the lines are curved as in Figure . . . ." How easily, from this point, Foucault might have hit on our Ronchi test.]

Making Rouge: "Dissolve steel wool in nitric acid, filter and mix with a filtered solution of oxalic acid. Precipitate oxalate of iron by heating. Filter, dry, and heat to igniting point. Result, a very fine, dark red rouge."—*H. A. Lower, San Diego, California.*

Breaking up Rouge: "Boiling lump rouge vigorously for an hour or so will reduce it to fine particles."—*Winston Juengst, Rochester, New York.*

Rigidity in Mountings: This was strongly urged by Porter, in "A.T.M.," where the tendency to provide too small a section at the "bottleneck"—the point at which the end of the declination axis joins the tube—was stressed.



Drawing by A. W. Everest

FIGURE 5

Polar axis of the "Old Town Pump" mounting. A better idea of the well braced rigidity afforded will be gained if a triangle is drawn, with its three vertices respectively near the lower end of the polar axis and the two declination axis bearings.

There is still another place where many designers whose bottlenecks are sufficiently large fail to put enough material to carry out the strength thus gained, and that is the metal plate which is often used for attaching the end of the declination axis to the tube. Plates only a quarter inch thick will flex on either side of the attached end of the declination axis, and plates half an inch thick are none too heavy. Note Figure 3, at the left, which shows both a blocky plate and ribs integral with the casting. The same figure, at the right, shows a hollow plate (shaped like a shoebox cover) at this point, but its side webs confer on it a large part of the rigidity of a solid casting—sufficient rigidity, at any event. The same feature is shown in Figure 4, where the tubeward end of the declination axis is a piece of heavy seamless tubing the full diameter of the declination axis (2⅞") welded to it as a "T" with a fairly long cross, at either end of which is a meniscus of ¼" steel welded on to receive the tube. Figure 5 shows the polar axis of the same telescope, with parts arranged in such a manner that the stresses are met with solid diagonal elements having a broad spread.

Another well-designed mounting, both mechanically and esthetically, is the one shown in Figure 6, made by H. D. Machonachy, of Westtown, Pennsylvania, who states that it stems from the 72″ at Victoria, British Columbia. The polar axis is a Ford banjo-type rear axle housing from which the rear semi-circle was cut and a similar forward half—the propeller shaft half—from a second housing substituted. The declination axis is a piece of 2″ steel shafting.

The mountings mentioned above are some of the best we recall seeing. Were the illustrations not needed in another place the photos of McCartney's

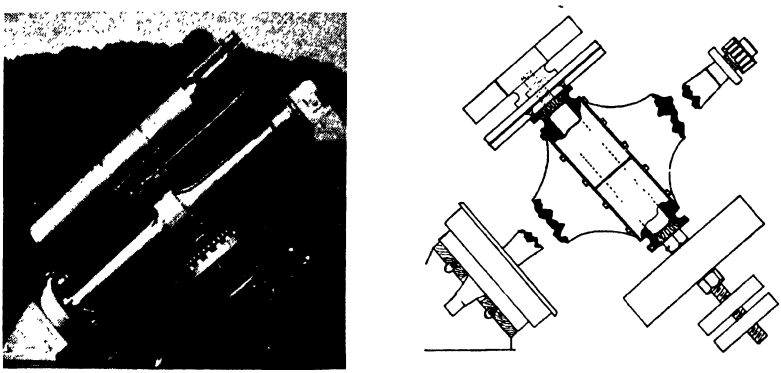


FIGURE 6

"Hemstead Hydrant" mounting (chapter on spring drives) would be included here.

However, for a full measure of all-wool-and-a-yard-wide ruggedness, see the mounting for the Schmidt camera at Mt. Palomar, designed by Porter (chapter on the Schmidt camera).

More attractive mountings than most of the above have been seen—that is, prettier ones—but there is danger that too much thought given to fancy trimmings will result in too little metal where it does the most good. Most of us will recall instances of this kind.

Star Disks in Telescopes: "The beginner is often desirous of seeing what a star-disk should look like in a telescope with an eyepiece of sufficient power. This can easily be managed by using two pieces of thin card (or better, metal), each with a small clean round hole about $1/40''$ in diameter. One of these is held to the flame of a lamp and looked at through the hole in the other; a star-disk with diffraction rings round it is seen with exactly the appearance of a star in steady definition through a properly adjusted telescope.

"It is also instructive to view a pair of such holes, set close together, through apertures of various size, ranging from $1/20''$ to $1/100''$ or less. This

will bring out very clearly the effect of enlarged aperture in reducing the apparent diameter of the diffraction disks and thus deciding the 'resolution' or otherwise of this artificial double star."—*W. H. Steavenson, in* Journal of the British Astronomical Association, *May 1936.*

Sodium Flame: "Twist a wire around a bunsen burner and continue it upward to the level of the flame, bending it into a ring which will encircle

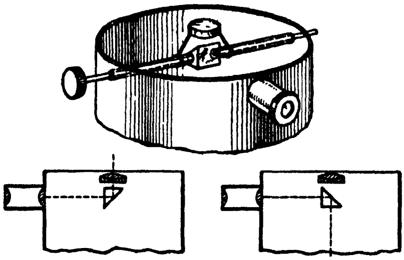


FIGURE 7

and almost touch the flame. Pack on the ring, in a kind of doughnut, a mixture of asbestos fiber, plaster of paris and plenty of salt. This will last for hours. When its brilliance diminishes, scrape off the surface."—*J. R. Haviland, New York.*

Conventions Used in Designing Objective Lenses: Sometimes these are confusing.

First, the refractive index: This is represented by the old Greek m, written μ (mew); often also by the Roman letter n, because of the resem-

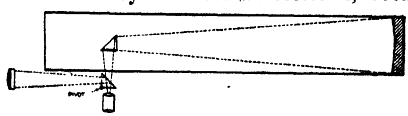


FIGURE 8

blance, and sometimes N. If there is an inferior letter below it, this refers to the spectral line (wavelength) designated. For example, n_d refers to the yellow d line of helium, having 5876 angstrom units wavelength, while nD refers to the yellow D line of sodium having 5893 angstrom units wavelength. Fraunhofer selected the more conspicuous lines or groups of lines of the spectrum and gave some of them capital letter designations like A (in the extreme red), B and C (in the red, the latter being the one also called Hα—to add to the confusion), D (which is in the yellow), E (in the green), F (in the blue), G (in the indigo—also called Hγ), H and K (in the extreme violet). Others on the spectrum map have small letter designations, like a, which lies between A and B, and b, which lies between E and F (the latter being designated Hβ); while d and g are used to designate other lines. The "system" is somewhat arbitrary and inconsistent, and designations are

now often stated in angstrom units. But the old lettered designations stick like a grass widow's traded-in name.

Secondly: Reciprocal of the dispersion. This is represented by the Greek letter ν (nu) but the Roman capital letter V is usually substituted because of the resemblance.

Finally, f_C (or f, cr) and f_F (or f, fl) mean respectively focus of crown and focus of flint. F generally refers to the combined foci of more than one curve, while the individual curves are usually designated by small f.—*Ed.*

Prism-finder Combinations: Several of these which have been described at different times in the Scientific American are collected here for con-

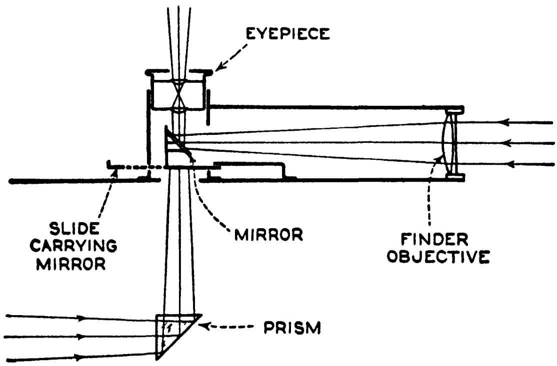


FIGURE 9

venience. Figure 7 is an arrangement by James Hart Wyld of Princeton University. The regular prism used as a diagonal carries the objective of the finder on a spider or bracket and can be rotated as shown, against stops. Figure 8 is an idea for pivoting a second prism so as to swing the light from the finder into the eyepiece of the telescope. M. C. Parks of Cleveland, Ohio, devised this. Figure 9 is by E. Lloyd McCarthy of Yerkes Observatory and its mechanism is obvious. Figure 10 is by Leo J. Scanlon of Pittsburgh. The back of the prism is silvered. After the description was originally published several readers of the Scientific American pointed out that its use—or rather the silvering of the hypothenuse side of the prism of the main telescope—would cause a certain loss in the light reflected to the eyepiece—probably small. As stated by A. R. K., "Why a prism is not totally reflecting when it is silvered: It all hangs on one of the little-known facts about metals. Nearly every substance, opaque or transparent, has a refractive index. The totally reflecting prism totally reflects when the material it is made of is of higher refracting power than the medium in which it lies—in this case, air. The refractive index of most metals is high, compared with that of glass—usually 3 to 6 or above—so the prism becomes much less dense with respect to the silver than would be the case if the prism were made of

air and surrounded with glass. Try coating the back of a prism with pitch and see what happens."

Big Reflecting Binoculars: A pair of full-sized reflecting telescopes may be used as a binocular, when suitably mounted. Herschel the younger (Sir John) once had a binocular made of two 6.3″ mirrors, each having an 86″ focal length. Capt. M. A. Ainslie of England now owns these mirrors. The binocular is believed to have been arranged as shown in "A. T. M.," page 441, at bottom. Commenting on this arrangement, Capt. Ainslie says (quoted

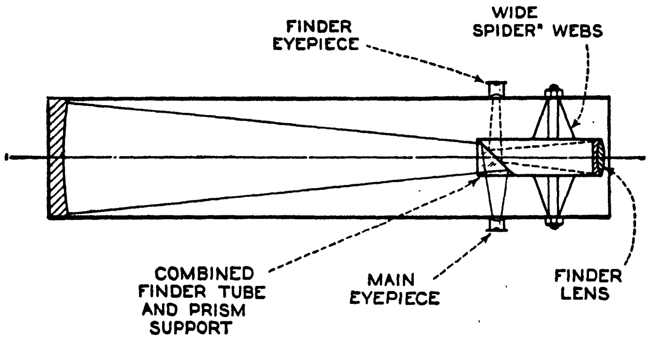


FIGURE 10

from *Scientific American,* Oct., 1932, p. 244): "One reason why this form of binocular never became popular must have been the difficulty of providing for variation in inter-ocular distance; peoples' eyes vary enormously in this respect. Also, if used for celestial objects, the eyepieces would come very inconveniently for the eyes, at any rate for objects at any considerable altitude.

"With regard to the binocular reflector made by one of your readers [the one shown at top of page 441, also on page 440, of "A.T.M."—*Ed.*] perhaps I may offer one or two criticisms: The first is that, as shown in use by Mr. Hanson in your illustration, the observer's head is so close to the mouth of both tubes that the heat radiated from it would be certain to cause currents of unequally heated air just at the point where they can do most injury to the definition. Over on this side we always make our telescope tubes project a considerable distance beyond the observer's head, for this reason. To show how powerful this cause may be in spoiling definition, I may mention that when the 24-inch Cassegrain which has been put up at Mill Hill, near London, is to be used visually, it is found necessary to put a screen of asbestos behind the mirror to cut off the heat of the observer's head, which is found to affect the figure of the mirror after a few minutes' observation if there is no screen. There would, however, be no difficulty in setting the tubes of the binocular farther apart, and carrying them up well beyond the observer's head, if thought desirable. Possibly with a low power, such as 65

diameters, the power mentioned in the account, the definition would not, after all, suffer very seriously from this cause; but with high powers I should expect serious deterioration.

"But, to my mind, a more serious objection to the plan adopted by Mr. Hanson is that there are an odd number of reflections before the image is

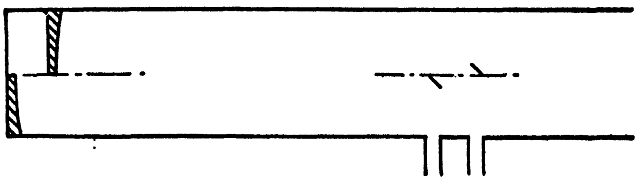


FIGURE 11

formed in the focus of the eyepiece. The result of this is that the image is reversed about a horizontal axis, but not about a vertical one: right remains right, but top becomes bottom. This appears to me to be a serious drawback, if the instrument is to be used for planetary or lunar observation.

"There is another point which has to be remembered by the designer of any binocular telescope; that is, that one must be quite certain that the

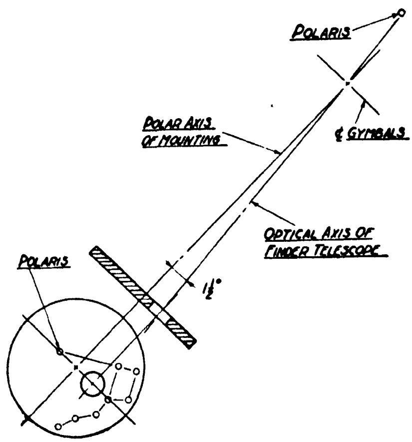


FIGURE 12

stereoscopic effect is preserved, and not reversed so as to become pseudoscopic. An example of what I mean is to be found in some binoculars which consist of two ordinary astronomical telescopes side by side: I have a pair of this sort, and the reversal of the relief is ludicrous on some objects. I have, for example, seen Venus apparently hanging *in front* of the distant land-

scape like a suspended lamp. The general rule is that, if the image is completely reversed (*i.e.*, both horizontally and vertically) then the left-hand telescope must supply the right eye, and vice versa; and the same applies if there is reversal about a vertical axis but not about a horizontal. Thus Mr. Hanson's telescope, if furnished with erecting eyepieces, would be pseudoscopic; right and left are, in each image, in their proper positions, but the right eye receives the image formed by the left-hand telescope (looking toward the object) and vice versa. To be truly stereoscopic, the images should be further reversed right and left. If completely re-erected, the result will be still pseudoscopic, for the reason just quoted."

The late James C. Critchett, of Banner, California, proposed the binocular shown in Figure 11, but did not live to make it. An ordinary mirror is

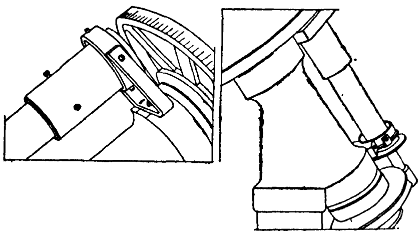


FIGURE 13

sawed in halves and the two "half moons" are mounted separately, at interocular distance.—*Ed.*

Celestial Pole Compensator: An arrangement independently hit on by Harold Towne, of Pittsfield, Mass., and Nathaniel B. Archer, of Green Bay, Wisc., was described in the May, 1935, *Scientific American* by the latter, and is worth putting on permanent record here. Mr. Archer wrote: "The polar axis finder is arranged to compensate, semi-automatically, the angular distance of 1°07″ between the celestial pole and Polaris. The constellation Ursa Major is represented upon a disk, which is revolved until the position of its markings corresponds to the apparent position of the constellation itself in the sky at the time. If the main mounting of the telescope proper is then adjusted until Polaris is seen at the junction of the cross-hairs in the polar-axis finder, the polar axis of the mounting will be found to be almost precisely parallel with the axis of the earth. The finder is mounted in gimbals (Figure 12) at its upper end, and the eyepiece draw tube is passed through an eccentric hole in a disk, which is rotatably mounted upon the frame of the equatorial mounting. This disk is engraved with a presentation of the constellation Ursa Major and Polaris.

"First, the mounting is roughly set into alinement with the celestial pole, and the triangularly placed handscrews on the base are turned down against the ground. By varying the relative adjustment of these hand screws, Polaris is brought to the intersection of the cross-hairs in the finder. As shown in Figure 13, if Polaris is seen at the intersection, then the polar axis of the instrument will be almost precisely alined upon the celestial pole."

Part II.

HAVING TO DO WITH SOME OF THE MORE PRACTICAL ASPECTS OF OBSERVING

His knees should bend and his neck should curl—
His back should twist and his face should scowl.
One eye should squint and the other protrude—
And this should be his customary attitude.

Theme song for the aching amateur astronomical observer, selected from the Harvard Observatory "Pinafore"; being a parody on the Gilbert and Sullivan light opera "H.M.S. Pinafore," written 1879 by Winslow Upton of the Harvard College Observatory and presented December 31, 1929, by members of the Observatory Staff at a New Year's Eve party of the American Astronomical Society on the occasion of its annual meeting. The drawing is by Russell W. Porter.

Researches With Our Instruments

Edward A. Halbach, M.S.
Milwaukee, Wisconsin

Possession of a thing is a great satisfaction to many people, but most of us must have a use for this thing or else discard it. Such is also the case with the amateur astronomer. Here we have a book on many types of accessories for the telescope you are contemplating or have completed. Unquestionably, there is great enjoyment and satisfaction in making the first telescope and studying the heavenly wonders through it. You make the rounds of the night sky several times, and soon the fascination dwindles and your 'scope' is relegated to the attic. Have you not already asked yourself, "What else is there to do beside putting the 'scope' away and waiting for the changing seasons to bring new stars to view?" The answer is, *plenty!*

With proper instruction and guidance, amateur astronomers and telescope makers can devote their spare time to productive astronomical researches, contributing much to this age old science. In 1935, the American Amateur Astronomical Association * (AAAA) was formed through the merging of a number of amateur astronomical and telescope making societies throughout the nation, for the express purpose of stimulating amateur participation in the existing research programs such as those of the American Meteor Society (A.M.S.) and the American Association of Variable Star Observers, (A.A.V.S.O.), and coordinating new programs that can be handled by amateurs with limited equipment or training. Leaders of the observing sections are spread throughout the United States and are always ready to lend aid where necessary.

Descriptions of the various research programs appear on the following pages, stating their purposes, giving the methods to be followed in carrying them out, and the names and addresses of those in charge of the programs. Though the descriptions are brief, they should suffice to give the reader a clear concept of each program and what equipment is necessary, should he desire to undertake the work.

Meteors

Among the many things that an amateur astronomer can do, even before he has a telescope, is meteor observing. Meteors and meteorites are the only material means man has of gaining information from the universe about us. Meteors are particles of matter, either metal or stone, or combinations of both, traveling through space and generally considered to be the debris of the universe, ranging in size from a dust particle to occasionally several tons. The average size is thought to be that of a grain of sand. Meteors

* The official monthly publication of the American Amateur Astronomical Association (AAAA) is *Amateur Astronomy,* which contains timely articles directly relating to the amateurs' work, reports from the various observing sections, and news notes from the affiliated societies. It is truly a publication by the amateur and for the amateur. Membership in the AAAA is $1.00, which includes the magazine *Amateur Astronomy.* Temporary headquarters are at 1312 E. Curtis Place, Milwaukee, Wisconsin.

are visible only when heated to incandescence as they shoot through the envelope of air surrounding the earth. If a meteor survives this heating and strikes the earth, it is called a meteorite.

"Of what value is meteor observing?" In the first place, as mentioned above, meteors are the only material samples of the universe about us, and we study this material through the light spectrum of the incandescent meteor and from the composition of the meteorite. Secondly, from the observed path of the glowing meteor much can be learned about our own atmosphere, its height and composition, its ionization at various levels, and the path and velocity of the meteor or meteor swarm. All this may sound a little difficult, but by following the observing suggestions and submitting the information to the proper authorities, one's work becomes of great value.

Meteor Counts: If one is to observe alone, begin by simply counting meteors, proceeding in the following manner:

1. Choose a place of observation with a horizon as free as possible, away from the city lights and smoke.

2. Provide yourself with a watch, flash light or lantern, pencil and paper.

3. Face in the same direction throughout the observing period, preferably east. If it is not practicable to face east, face south, north or west in order of choice. Do not observe if the moon is above the horizon between the ages of 7 and 21 days (first and last quarter).

4. The unit must be the number of meteors seen per hour by one observer. Try therefore, if possible, to observe several consecutive hours. Three hours on any given night adds much to the value of one's work. It makes no difference at what minute you begin, provided you go a whole number of 60 minutes therefrom. On some nights take the period in the early hours, on some the latest hours of the night. Observations during the hours just after dark, though meteors are few, are very important; also those just before dawn.

5. Make a time record to the nearest minute, of every meteor seen.

6. Also make an estimate of the time lost unavoidably and in recording each count, noting the same on the data sheet so that allowances can be made when determining the rates.

7. In your report include a full account of the condition of the sky for each hour by (*a*) recording the magnitude of the faintest star easily seen in the region observed, and (*b*) an estimate of the fraction of the area of observation covered by passing clouds, with times at which they interfered.

8. Always give the double date for the night, so that there can be no ambiguity. For example: August 10–11, meaning the night starting on the civil date August 10, ending on August 11. Count hours consecutively through midnight, *i.e.*, 1:00 A.M. equals 13 hours, 2:00 A.M. equals 14 hours, etc.

9. Blanks for recording these data may be obtained from Dr. Charles P. Olivier, President of the American Meteor Society, Flower Astronomical Observatory, Upper Darby, Penn., and all reports should be submitted to him. The A.M.S. encourages the careful observation of meteors, collects

and files records, gives personal aid where needed, and gives due credit in its publications to each contributor.

Plotting Meteors: Meteors are known to appear in definite groups or showers, which travel in elliptical orbits about the sun and appear at certain seasons of the year. If the apparent paths of the meteors seen during one of these showers are plotted or traced on star maps, and these traces projected backward, as shown in Figure 1, they are seen to emerge from ap-

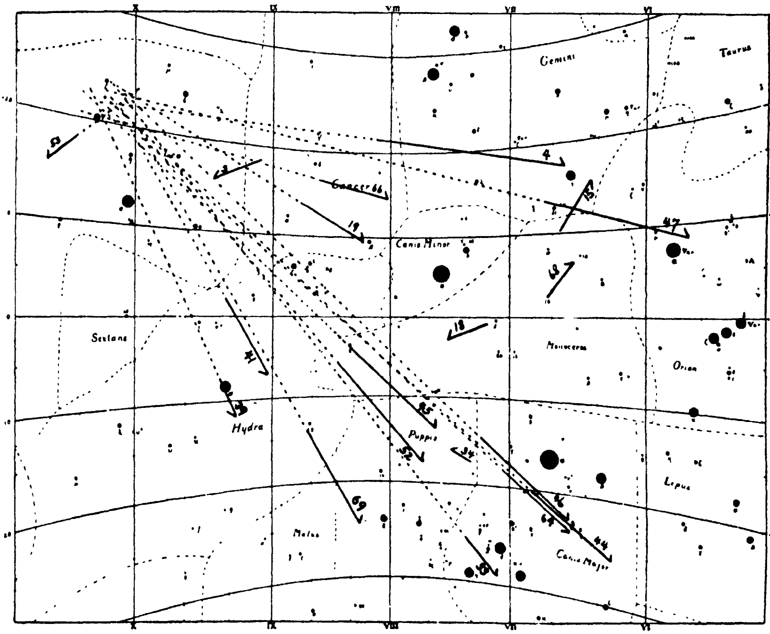


FIGURE 1

Meteor traces, showing a radiant.

proximately the same point, the radiant. The shower is usually named after the constellation in which the radiant is located. The radiants for most of the showers are found to shift slightly from night to night and new showers frequently appear. Major meteor showers are being observed by hundreds of people throughout the world, but the many minor showers and sporadic or stray meteors are passing unobserved. To the astronomer, these less spectacular displays are of as great importance as the major showers, as they give us somewhat of a cross-section of the density of cosmic material in space. There are many sporadic meteors which, if plotted, would determine new radiants, or confirm already poorly established radiants.

To plot these meteors approximately is not difficult but practice is needed to become a good observer. The following directions should be observed:

1. Choose a place of observation with a horizon as free as possible from the city lights and smoke.

2. Provide yourself with a watch, flash light or other dim light, pencils, straightedge, record blanks, and a set of star maps. Of the 13 star maps furnished by the A.M.S. generally only three to five are used on one night. The record blanks are furnished with the star maps on request. Maps may conveniently be held down by weights or clips, or better by mounting them on stiff cardboard.

3. On the maps furnished plot each meteor as seen. The meteor path is to be shown in length and direction by an arrow in pencil on the map; thus $\xrightarrow{3}$, with the proper serial number for the night inside the half arrow, as shown.

4. Only experience will show how to trace the meteor's path correctly upon the map. The problem is to determine accurately the beginning and end points of the path. Joining these points gives the correct trace on the map. Hence, if a meteor begins and ends exactly at two stars, the trace gives no trouble. Most paths are not so conveniently placed, so when a meteor is seen, do not remove your eyes form the spot until an accurate mental picture of the meteor's length and path has been made. Then refer to the star map. A method that is recommended for most conditions is as follows: determine some one point on the meteor's path, then glance backward or forward along the ruler or straight edge held at arm's length parallel to the path in the sky, and pick up some star in the direction in which it seemed to go. The original selected point and this star then determine the direction of the path. From the first point, estimate how many degrees of the path lay before it and how many behind it, and plot the path as accurately as possible. This method, used with care, largely eliminates the projection errors, especially if the meteor is far from the radiant.

5. Use the record sheet, recording with the serial number of each meteor, the time it appeared (hr., min., and sec.), brightness in magnitude, color if possible, duration in tenths of a second, and duration of train, if any.

The principal meteoric showers of the year, reprinted from the *American Meteor Society Bulletin No. 15,* are tabulated below.

Shower	Date of Maximum	Duration in Days	Hourly Rate
Quadrantids	Jan. 2	4	28
Lyrids	April 21	4	7
Eta Aquarids	May 4	8	7
Delta Aquarids	July 28	3	27
Perseids	Aug. 11	25	69
Orionids	Oct. 19	14	21
Leonids	Nov. 15	7	21
Geminids	Dec. 12	14	23

Duplicate Height Observations: Duplicate observations of meteors made during showers are of great value. The main requirement is that two or more observers be stationed about 30 to 90 miles apart and watch the same area about 60 miles above the earth's surface. Any bright meteors appearing in this general area are likely to be seen by two or more of the coöperating observers. The same directions as under "Plotting of Meteors" are to be followed, using the same maps and data sheet. The time of occurrence is here of prime importance, for it is the principal means of identifying those meteors seen simultaneously from the several widely separated observing points. Because the time is so important, several methods of coördinating time measurements can be used. One possible method is to note the time of the first brilliant meteor seen at the beginning of each hour or half hour period, and then compare these times after data sheets from the several observing stations are assembled. Thus any differences in the setting of the individual timepieces are found and corrections applied to all the meteors plotted.

Since one cannot simultaneously look at the timepiece and keep his eyes on the region where a meteor was just seen, a second person should act as recorder to note the time and make all records other than the actual plot. The writer has constructed for the Milwaukee Astronomical Society a recording timer which eliminates the need for the second person [described in the following chapter.—*Ed.*] With the recording timer, one person makes all records of data for as many as four observers. In cold weather he remains indoors, two way communication being provided through telephone headsets and breastplate microphones. Time records are very accurate, as the observer simply pushes a button switch in his hand on seeing a meteor, a printed time record being made by the instrument.

To know what area of the sky to watch is of prime importance. Persons intending to participate in this program may get this information by submitting a description of their observing locations to Dr. Olivier, who will either furnish the necessary instructions or refer them to the regional director in their area.

Telescopic Meteors: A statistical study of telescopic meteors is at present being carried on jointly by the American Meteor Society and the American Association of Variable Star Observers. In general, observations are made in conjunction with variable star work. As mentioned on page 532, the variable star observer should note, in addition to the variable star data, the number of minutes actually spent in looking at each field, and immediately his routine observations become of great value in the telescopic meteor study. When a telescopic meteor is seen in the variable star field, the following information should be jotted down:

1. Date: Give double date, as Aug. 10–11.
2. Time: Give hr. and min.
3. Position of observed area: Show designation number on variable chart.
4. Magnitude: Estimate only to whole magnitude.
5. Direction of motion in degrees—*i.e.*, position angle toward which meteor

is moving: Read from north, 0°; through east, 90°; south, 180°; west, 270°.

Information and data sheets will be provided by the A.M.S. or the A.A.V.S.O., or through the AAAA.

Meteor Photography and Spectroscopy: Although this work is very new, it is unquestionably becoming of greatest value to meteoric astronomy. The equipment needed is a hand camera of speed $f/6.3$ or better, and fast photographic emulsions. Cameras may be stationary or on a driven mounting. To obtain meteor spectra a wedge prism of about 30° must be used in front of the camera lens. Great patience is a prerequisite, for it was found that even during the heaviest showers, an average of six to eight hours' exposure was necessary for each meteor photograph.

The Perseids and Leonids are the best displays and can be expected to give the most fruitful results in meteor and spectrum photography. For more complete details, see the chapter "Meteor Photography" by Peter M. Millman.

Novae Search Program: The discovery of Nova Herculis, in December 1934, aroused new interest in novae type stars. Astronomers are especially anxious to catch the next ones earlier in their rise. The A.A.V.S.O. director for such a program is named in the list at the end of the chapter.

The program requires that one become familiar with all the stars in an assigned area 10 degrees square, and study this field at every opportunity, making a record of the date, time, faintest star visible, and noting whether anything unusual is seen. Maps and area assignments are obtainable from the program director. In the event that any observer notes a new object in the assigned field, it is urgently requested that he call or send a telegram to the nearest observatory or directly to the program director, requesting the receiving telegraph operator to have the message phoned immediately to the addressee.

Planetary: Interest in planetary observations has been revived by the Planetary Section of the AAAA, under the director named in the list at the end of the chapter. The activities of this section include observation of planetary detail, changes in lunar detail, comet seeking, asteroids, solar phenomena, etc.

Variable Stars

The term variable star is not new to most persons. From time to time, new stars or novae become visible to the unaided eye. These new stars are usually classified as variables and astronomers, amateur and professional, systematically follow their light variations. After sufficient time has passed and it becomes known to what extent they vary, we may also be able to learn or reason why they vary.

Algol, an eclipsing variable star, is one of the oldest known and one of the simplest type of variable. Variable stars are classed according to the type of variation. The typical light curves of Figure 2 are composites of observations submitted mainly by amateur observers around the world. Certain types of variable stars lend themselves well to observation by

amateurs, because of their brightness ranges and general characteristics. Furthermore, because of the wide distribution of amateurs, these stars can be watched closely at all times, leaving few unobserved periods, a task that is almost impossible for the limited number of observatories that could follow their variations. Hence the A.A.V.S.O.* was formed to carry on the ever increasing task of accumulating and compiling the data.

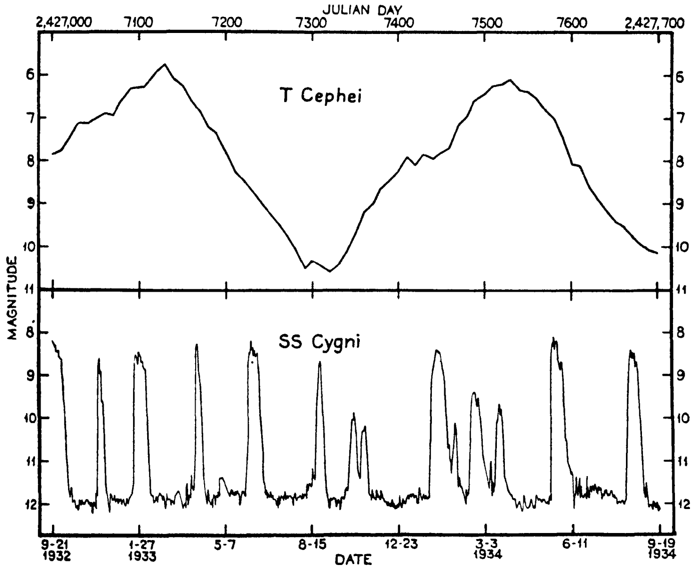


FIGURE 2

Light curves of typical variable stars.

Star charts of fields including the variables are obtainable from the A.A.V.S.O. at a nominal cost. The accompanying chart of "U Herculis," Figure 3, is a reproduction of one and will be used to introduce the method of observing. Six other easy fields that the beginner may obtain and try are listed below. Only a faint knowledge of the constellations is required to find these variables.

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* The A.A.V.S.O. (American Association of Variable Star Observers) with headquarters at Harvard College Observatory, Cambridge, Mass., functions for the sole purpose of encouraging and guiding the amateur in the observation of variable stars, compiling, publishing and analyzing the observations. Occultations, photographic studies of variables, and visual and photographic search for new stars are also a part of the A.A.V.S.O. activities. Leon Campbell, astronomer at the Harvard College Observatory, will provide information and assistance upon request.

Name	Designation No.	Name	Designation No.
W Cas	004958	U Ori	054920a
W Tau	042215	RCrB	154428
T Ori	053005a	VUMa	090151

Referring to the chart of "U Herculis," one notes at the upper left hand corner the designation number 162119, meaning that the star is located

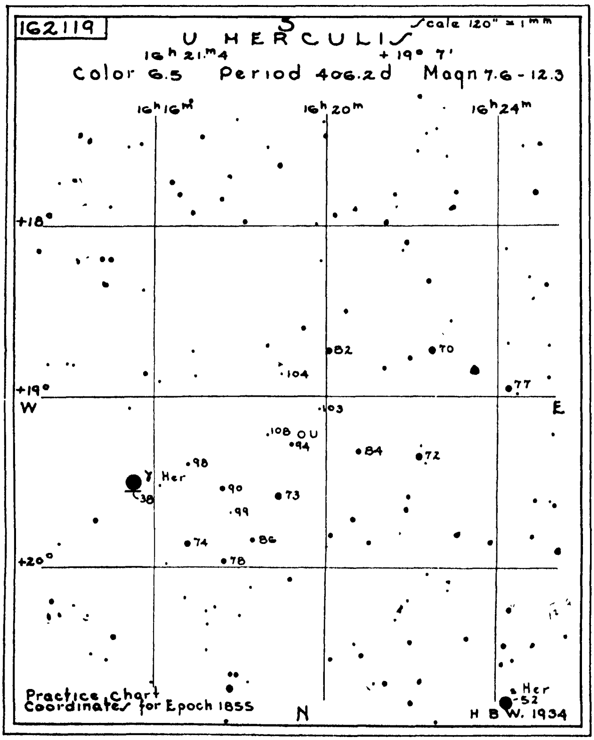


FIGURE 3

in right ascension 16 hours 21 minutes, declination north 19 degrees. If the last two digits are italicized or underlined, as 1621*19* or 1621<u>19</u>, the declination is 19 degrees south of the celestial equator.

On all the charts furnished by the A.A.V.S.O., Greek letter designations are given to the brighter stars to correspond with ordinary star maps. The brightness of each star in the field is indicated roughly by the size of the dot,

comparison stars being indicated directly in magnitude, as 74, 78, 90, etc., indicating that they are stars of magnitudes 7.4, 7.8, 9.0, etc. The variable itself is usually on or near the center of the chart and indicated by a dot in a circle.

Before one actually attempts to look for a variable, some time should be devoted to becoming familiar with the star charts. Take the "U Herculis" chart to the eyepiece of the telescope and first establish the east-west line in the eyepiece. This is done by getting a bright star into the field of view and noting the direction it moves. It will enter the field from the east and pass out on the west, so place the chart adjacent to the eyepiece, with the east-west line on the chart corresponding to the direction of travel of the stars in the eyepiece. North-south will then be correct for the Newtonian reflecting telescope, and in some positions of the refractor.

The next step is to ascertain the approximate size of the field of view of the telescope with the different oculars. Always use a 1″ or longer focal length eyepiece at the start. Point the telescope at the region not far from the celestial equator and, without moving the instrument, note the time required for a bright star to pass across the field from edge to edge. Stars near the equator move 1° in 4 minutes, so, if the observed time is four minutes, the field is 1° and thus includes the area within a square on the "U Herculis" chart.

Now to find the variable "U Herculis." From a star map locate γ Herculis in the heavens and get it in the field of view. This will be your starting point or port in the sky. Now slowly sweep in the direction of the variable, identifying stars in the field until you find a configuration or grouping of stars which matches stars shown on the variable star chart. Do not be discouraged if it takes you an hour to find the variable the first time, as the next time it will take you only 15 minutes and eventually only two or three minutes.

Although circles on the telescope mounting are not a necessity, they do make the finding of variables much faster, once the procedure is understood. With circles, the polar axis need be only approximately adjusted to point to the celestial north pole, if the differential method of star finding is used as explained here. With the "U Herculis" field, get γ Herculis into the field of view, as before, and move the telescope tube 4′ east and the variable should be in the field of view. If in other variable fields there are no bright stars, find from a star atlas the nearest naked-eye star which has its position given in some ephemeris or star catalog available. From the right ascension of the variable, subtract the right ascension of the bright guide star, and if the difference is negative the telescope tube is to be moved east by that amount, if positive, move west that amount. Differences in declination are obtained likewise, remembering to note whether to move the 'scope north or south of the guide star. Once determined, the differences in R.A. and Decl. should be noted on the corner of the chart for use the next time. Circles, although not a prerequisite, make for a speedier finding

of variables, for one cannot hope to rely on memory in locating the 400 or more variables for which the A.A.V.S.O. has prepared charts.

Before attempting to estimate the brightness or magnitude of the variable, one must become familiar with brightness of stars as they appear in one's telescope. On the chart, comparison stars are designated by numbers indicating their brightness in magnitudes, to tenths. One must also try to get some concept of what a difference of one magnitude means—a difference of approximately 2.5 times in brightness.

Having located the variable, select at least two comparison stars, one a little brighter and the other a little fainter than the variable, and estimate how bright the variable is in terms of these two stars. Although this may seem difficult at first, precision in estimates is quickly attained. Record exactly what you see, regardless of seeming discrepancies in your observations. In making your estimate, *always* turn the head so that the two stars being compared appear side by side, *never* above or below each other, also equidistant from the center of the field. The human eye fails to make exact comparisons if the above rule is not strictly followed. Some observers prefer alternately to place the variable and the comparison star in the center of the field for comparison, especially with widely separated stars. Also, red stars are best observed by a quick glance. Staring at a red star causes it to appear brighter than it actually is.

Having determined the brightness of the variable to tenths of a magnitude, note the time of observation and enter this information on some form of record, including also the size of telescope, date (Julian date preferred), comparison stars used, also the actual number of minutes that you were looking through the eyepiece while making the observation. The latter information is very valuable for the statistical study of telescopic meteors.

At the end of the month, all observations should be sent to the A.A.V.S.O. headquarters, which furnishes the standardized form for these records. For star charts and general information, communicate with Leon Campbell, A.A.V.S.O. Recorder, Harvard College Observatory, Cambridge, Mass. The AAAA stands ready to offer any assistance needed in placing a prospective observer in contact with an experienced observer in his territory for personal assistance.

Photographic

Patrol Program: In speaking of celestial photography, one usually thinks of photographing the moon, a few planets, and star constellations. Seldom has the amateur seriously attempted a real research program with photography, due perhaps to the lack of guidance. A photographic section of the A.A.V.S.O. was established in 1936, to foster and guide a coördinated photographic program, particularly for patrol work and the study of cepheid variables, and is under the direction named in the list at the end of the chapter.

A small hand camera can do exceptional work in patroling the sky. The object of a photographic patrol is to discover novae, asteroids, comets,

and any unusual changes which may occur. It is estimated that 10 to 20 novae brighter than ninth magnitude appear each year, but very few of these are ever discovered, simply because an adequate patrol is not maintained. Small cameras usually cover a large angular field and if the lens is a good one, star images may be good almost to the edges of the field. A large diameter lens is of course desirable, although even small lenses will do surprisingly well. A first class lens with 1″ effective aperture will record ninth magnitude stars in 10 minutes' exposure on a clear night using fast photographic emulsions.

A complete hand camera is not a necessity—in fact, it is generally more satisfactory to mount a good lens in one end of a box, at the opposite end of which are mounted the guides for the plate holder. Plates must be used because roll films and cut films will not remain sufficiently flat for this work. Provisions of course, must be made for adjusting the focus, and for alining the plate perpendicular to the optical axis of the lens. A home-made arrangement of this sort can be made more rigid and with more stable adjustments than the best of hand cameras.

The camera may be fastened rigidly to your equatorially mounted telescope, and the telescope with its polar axis in accurate alinement with the pole may be used for guiding. An eyepiece for guiding may be constructed by fixing cross-wires on a diaphragm ahead of the objective lens of any positive eyepiece, so that they appear sharply in focus through the eyepiece. Single silk fibers make good cross-wires when waxed to a cardboard ring which is inserted in the eyepiece to the proper distance.

A simple way of making a focus adjustment is to take an exposure of, say, five minutes' duration, with the camera fastened to the guiding telescope. The camera shutter is then closed and the camera is moved slightly—enough so that the star images are displaced about ½ mm on the negative. The focus adjustment is changed to a new value and another five minute exposure is taken, using the same guide star as for the first exposure. This is repeated for five or six trial adjustments, and for the last exposure the displacement of the camera made twice the previous value in order to identify which image corresponds to a certain focus adjustment. An accurate record must be kept for the various exposures, in order to correlate them when the negative is developed. Figure 4 shows an adjustment plate, image No. 3 being chosen as the best focus adjustment.

The images on the developed negative are studied with a magnifier and the smallest image in a group is selected as the correct focus adjustment. From this plate it will be easy to decide whether the plate is square with the lens, and just how much displacement is necessary to correct it. Generally it will be found that the images in the center of the field are not in focus at the same adjustment as those at the edge. The usual procedure is to use the focus adjustment which gives accurately focused images in a circle one-half to two-thirds the width of the plate in diameter.

The procedure to be followed in a photographic patrol will be to assign several sky areas to each observer, who will photograph these areas once

each night or as often as possible, always using one particular guide star for a particular area.

When the plate holder is removed from the camera, after an exposure has been made, the plate holder slide is drawn about a quarter inch while in the dark. The number of the plate and the position of this edge of the plate (north, east, etc.) are written on it with a pencil, using a moderate amount of pressure. The pressure of the pencil on the emulsion leaves a mark which will develop in the usual manner. By thus identifying the plate

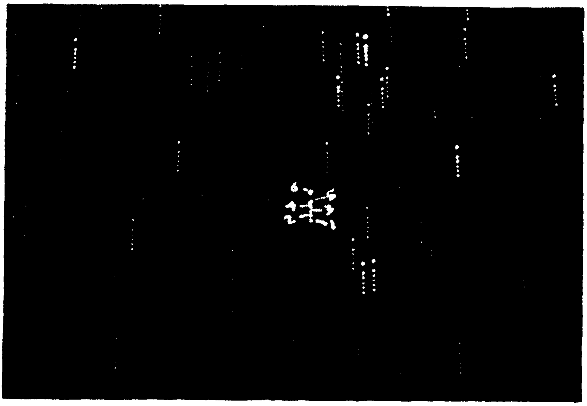


FIGURE 4

Focus adjustment plate for patrol camera.

and recording the details of the exposure in a data book, it is possible at any future date to refer to the plate with complete confidence. Develop negatives in contrast developer.

Make it a rule to make a record of all the data pertaining to every astronomical photograph taken, for one cannot tell in advance whether a negative will be of great value or not. It is almost impossible for a record to suffer from too much data; but it is unfortunately true that a good many observations suffer from a lack of completeness in the data. Even negatives taken for adjustment should be carefully recorded, using the same care one would use if he knew that the negative would show the initial outburst of a nova.

It is preferable that the exposure time, type of emulsion, development, etc., of all negatives of a particular area be identical, in order that accurate comparisons can be made between negatives. Two negatives of the same area may be compared by superimposing them so that the star images are almost in coincidence. The negatives are then gone over with a magnifier, image by image, comparing the new negative with the original one. If any obvious changes are found, they should be noted and the proper

persons notified immediately that a possible discovery has been made. One should be cautioned, however, in announcement of a discovery from a single negative, since occasionally defects, pinholes, scratches, etc., appear which are misleading. Better to wait until two negatives definitely indicate that a change has taken place in the sky before announcement.

It is very convenient to have a small motor-driven equatorial mounting for the patrol camera. Once adjusted it needs no guiding for the patrol work, as small discrepancies in the drive do not show in the star images produced by the short focal-length lens of the average hand camera.

Cepheid variable program: The more experienced or enthusiastic amateur may do more advanced work, particularly in the study of cepheid variables. For this work it is advisable to use larger lenses than in the patrol work, for in many cases the variables are as faint as the thirteenth magnitude. Old rapid rectilinear or Petzval type lenses serve the purpose well. The lens chosen should have a clear aperture of 2″ or larger if possible. Focal length is not so important, though the longer focal length gives the greater separation of star images on the plate, which is often desirable.

In the cepheid program work, sharpness of the star image on the photographic plate is of prime importance, hence guiding of the camera must be very exact. As in the patrol work, the camera may be attached rigidly to the back of a telescope of focal length several times that of the camera lens, thus minimizing the discrepancies in hand guiding. The real solution to guiding is a rigid and carefully constructed, driven equatorial mounting for the camera and a small aperture guide telescope.

In this work, the lens needs to cover only a small field, a 2½″ x 3½″ plate being large enough for a lens of 12–15″ focal length, a 4″ x 5″ plate for a lens of 20—30″ focal length. Although star images beyond the central area of the photographic plate may not be focused with sufficient accuracy for this work, larger plates may be used, thus simultaneously serving for the patrol work. In using only the central area of the plate, the camera need be only a stovepipe with several light baffles on the inside. Focus adjustments are to be carried out precisely as in the patrol work.

If one can obtain suitable equipment, and desires to participate in the cepheid program, he is advised to communicate with the director of the photographic section, who has been assigned by the A.A.V.S.O. to coördinate the entire photographic program—see list at end of chapter. At the present time, all photographic plates taken under this program will, if so requested, be reduced by Mr. Matthias on a modified Schilt microphotometer of his own construction. Monthly photographic notes by the director appear in *Amateur Astronomy,* the official publication of the AAAA.

Occultations

For the amateur who finds that the time he can devote to observing is very limited, there is a fine program to which he can contribute much, namely, "Occultations." Prof. Dirk Brower, an authority on the subject, wrote a

comprehensive article in *Amateur Astronomy,* Jan. 1936, p. 2, which is reprinted here in part.

"A remarkable and a very encouraging feature of astronomical research of the present time is that it is still possible to make valuable contributions with modest instrumental equipment. . . . A possible program for the user of a small visual telescope is the observation of occultations of stars by the moon.

"The moon's traveling eastward among the stars will cause the disappearance of stars along its apparent path in the sky. Owing to the absence of an appreciable atmosphere on the moon these disappearances are instantaneous. Noting the exact time of disappearance of a star covered by the moon is called the observation of an occultation. Within about an hour after the disappearance the star will reappear from behind the western limb of the moon. The observation of a reappearance is more difficult and, as a rule, less reliable than the observation of a disappearance. This is especially the case before full moon, when the disappearance takes place at the dark limb. It has been found that the observations of disappearances that take place from immediately after new moon to about two days before full moon are so far superior in accuracy that an observer can safely limit himself to these observations.

" . . . the main requirement for securing a useful observation is that the time be accurately recorded. It is sufficient if the observed time is accurate to within half a second. Simple as this may seem, the care necessary to obtain this accuracy should not be underestimated. The observer must record his time with the aid of an accurate clock or chronometer, either by the eye-and-ear method or by using a good stop watch as an auxiliary time piece. The clock should be compared with accurate radio time signals, preferably both before and after the observation, and should maintain a constant rate between comparisons. The procedure is straightforward, but requires practice and careful testing of the timepiece used."

Not all radio time signals are accurate. Most reliable are those from Arlington, which transmits hourly signals on a number of wavelengths. Time schedules and frequency of transmission may be obtained directly from the Naval Observatory, Washington D. C. The author has constructed a recording timer for use in observing occultations and a complete description of the instrument appears in the next chapter. Operating from a 60-cycle frequency-controlled lighting circuit, and checked with radio time signals before and after observation, the timer greatly simplifies the making of an accurate time record.

"The additional data necessary in the reduction of the observation," Professor Brower continues, "are the geographical longitude and latitude of the observer. These data must be known to within two or three seconds of arc. This is done once for all, by referring the position of the observatory to some spot within a few miles which has been accurately located by the Coast and Geodetic Survey.

"From two such observations made within a few hours the position of the

center of the moon at any instant near the time of observations can be calculated. Usually the results derived from a great number of observations made by different observers are combined into a single mean. The advantage of this procedure is that the erratic effect due to the irregularities of the moon's limb is then practically eliminated.

"About a thousand observations are now observed each year by numerous observers in many different countries. The compilation and discussion of these results during the past 12 years has served to determine the exact position of the moon with an accuracy far exceeding that in the past.

"That the theory (Prof. E. W. Brown's mathematical theory of the moon's motion) fails to represent the moon's motion exactly must be ascribed to the fact that the earth's rate of rotation is not uniform. This explanation was suspected for over 50 years but the proof was lacking until fairly recently, when overwhelming evidence in favor of this explanation was obtained from observations of the sun, Mercury, Venus, Mars, and Jupiter's satellites.

"At any time the earth may change its period of rotation. The occultation results will show this better than any other series of astronomical observations. With the abundance of data now being accumulated we may expect to be able to study such a change in detail and possibly find a definite clue to the causes of these changes.

"This is the most immediate purpose of the occultations. Numerous other results can be obtained from the available data. The collection of observations will become the more valuable the longer the present campaign is continued."

Approximate predictions of occultations at any location can be obtained from the "American Ephemeris." Results of all observations are to be submitted to Prof. Dirk Brower, Yale University, New Haven, Conn. Either Prof. Brown or the AAAA is to be consulted for special help.

A great need exists for volunteer computers to reduce the observations of those not able to do so themselves, but persons interested in observing will certainly not be discouraged. This work calls for a knowledge of the rudiments of geometry and trigonometry and a certain amount of facility with the use of tables. An "Ephemeris and Nautical Almanac" for the year in which the observation was made and a convenient log and trig table are necessary. With the accumulation of a little skill, the reduction of an occultation can be completed in somewhat less than an hour.

Amateurs who might be interested in either phase of this work, are invited to communicate with Prof. Brower of Yale or with the AAAA, whose main purpose is to assist beginners in the field of amateur astronomical research.—*2346 North 47th Street.*

American Association of Variable Star Observers (A.A.V.S.O.)

Variable Stars—Leon Campbell, Harvard College Observatory, Cambridge, Mass.

Novae—L. E. Armfield, 1410 Marshall Street, Milwaukee, Wis.

Occultations—Prof. Dirk Brower, Yale University Observatory, New Haven, Conn.

Photographic—Lynn Matthias, 2121 E. Capitol Drive, Milwaukee, Wis.

General Information—Leon Campbell, Harvard College Observatory, Cambridge, Mass.

American Meteor Society (A.M.S.)

Meteors—Dr. Charles P. Olivier, Flower Observatory, Upper Darby, Pa.

American Amateur Astronomical Association (AAAA)

Planetary—Ed Martz, Jr., 726 N. Elmwood Ave., Oak Park, Ill.

General information concerning all observing programs—*Amateur Astronomy* Publications Headquarters, 1312 E. Curtis Place, Milwaukee, Wis.

The Author.

A Recording Timer

EDWARD A. HALBACH, M.S.
Milwaukee, Wisconsin

Accurate timing of occultations and time coincidences in duplicate meteor work has always presented great difficulties for the amateur astronomer. The writer has solved the problem for members of the Milwaukee Astronomical Society by constructing a recording timer which prints directly on paper the exact time of any phenomenon to within one-half second. Of course, it must be remembered that the accuracy of the recording timer is only as great as the frequency control of the lighting circuit to which it is

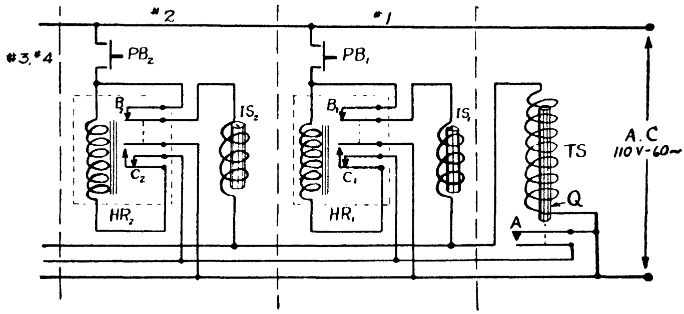
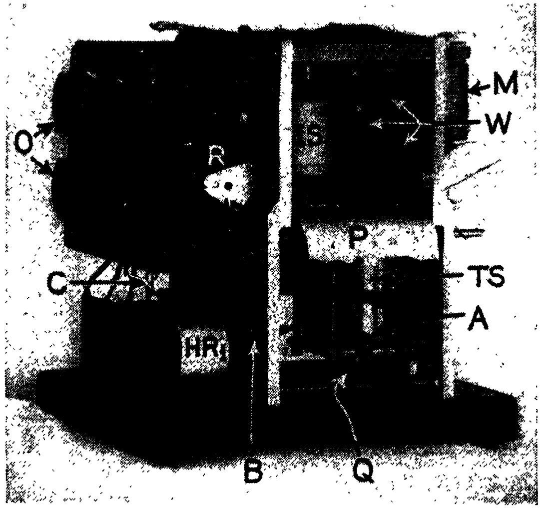


FIGURE 1
The circuit diagram.

connected. Not only can it be used by an individual observer, but by as many as four simultaneously, each recording an identifying number in addition to the time record. For meteor showers during cold weather, the instrument is a great asset since, through its use, but one person is required to record all information other than the actual meteor plots. This is done by placing the recording timer indoors and using a 5-wire circuit to connect the observers' push buttons with the instrument. All information to be recorded is transmitted between observers and the person recording through telephone headsets and breastplate microphones. Uses for this instrument in observing programs are explained in the section on "Researches with Our Instruments."

The circuit diagram, Figure 1, shows the operating principles which are: Observer No. 1 punches a pear-shaped push button PB_1 in his hand, operating the time punching solenoid TS and the observer's identification solenoid IS_1 which are in series. As the plunger of TS reaches the top of its travel, contact A is closed, energizing the holdout relay HR_1. As HR_1 closes, contact B_1 is opened, de-energizing TS. Contacts at C_1 keep HR_1 closed until released by releasing PB_1. If two observers punch time at the same instant, both of their identifying numbers are recorded with the same time record.

When HR_1 closes, the time punching solenoid TS is immediately free for another time record by any or all of the three other observers, irrespective of whether or not PB_1 is released. The action of TS is instantaneous, giving a quick blow to the printing platen. The circuit diagram shows the relays HR and identifying solenoids IS for only two observers, the remaining two sets are not shown, as they are the duplicates of No. 1 and No. 2.



Photographs by the author

FIGURE 2

Front view. A, B, C are contacts (see also Figures 1, 3, 4); HR, hold-out relays (also Figures 1, 3, 4); IS, identifying solenoids (also in Figures 1, 3, 4); M is the synchronous clock motor (also in Figures 3, 4); O, connections to push buttons PB of Figure 1 (also in Figures 3, 4); P is the paper (also in Figure 3); Q is the plunger of the time punching solenoid TS (also in Figure 1); U, pawls moving minute and hour wheels (not shown above—see Figure 3); W, time wheels (also in Figures 3, 4).

The heart of the unit is a set of three numbered wheels W (Figures 2, 3, 4) the seconds and minute wheels numbered from 0 through 59 and the hour wheel, 1 to 12, repeated five times. A synchronous clock motor M (Figures 3, 4) similar to a Telechron unit, the spindle of which makes one revolution per minute, is geared directly to the seconds wheel. The raised numbers on the wheels are electrotyped strips, 'zinc high', tacked to the periphery of Bakelite disks. These strips can be obtained from any electrotype shop or through your printer. A pawl operated by a cam on the seconds wheel, engages with the ratchet wheel on the minute wheel once each minute, moving it one number. Another pawl operating with the first, engages with the

ratchet wheel on the hour wheel to move it once each hour. These pawls and ratchets are shown in the accompanying illustrations, especially in Figure 4.

As shown in the illustrations, time records are made on adding machine paper which is purchased in rolls. After each record, the paper is moved forward about ½″ by the energy of the dropping plunger Q after the impact on the printing platen. The observer's identifying number is recorded simultaneously with the time by the solenoid IS through a simple leverage, quite similar in operation to a typewriter. A typewriter ribbon passing at right angles to the travel of the paper above the printing platen, between the paper

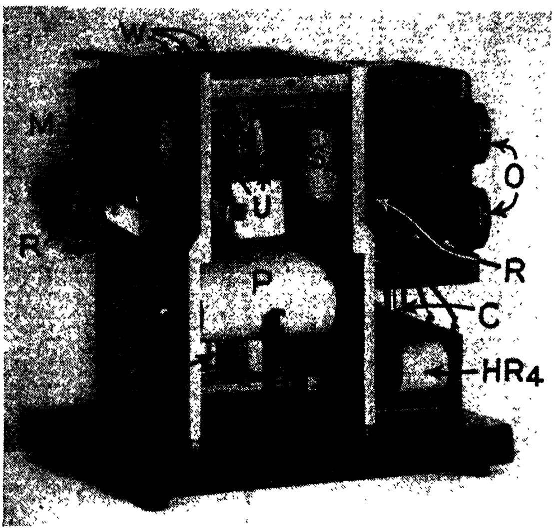


FIGURE 3

Back view.

and the numbered wheels, makes the imprint legible. It is moved slightly after each imprint, simultaneously with the moving of the paper strip.

The main solenoid TS, of 1250 turns of No. 24 B.&S. gage cotton enameled wire, is wound on a ⅜″ I.D. thin-walled brass tubing and fits a 2″ length of 1½″ pipe. End plates on the solenoid are also of soft iron. The plunger Q, ⅜″ in diameter, is drawn up into the solenoid, striking a rubber-covered platen under the numbered wheels. The platen has a rubber pad to prevent the flattening of the soft copper electrotyped numbers during use. Contact A and the mechanism for moving the paper and typewriter ribbon are linked with the lower end of this plunger.

The holdout relays, HR_1, HR_2, etc., (Figure 1) although noisy in opera-

tion, work well in spite of the fact that they were made for D.C. operation. They are of the ordinary clapper type used in old "B" eliminators and rewound to operate on 110 volts A.C. instead of 6 volts D.C. Perfectly silent A.C. relays of the telephone type are available but rather expensive. Struthers and Dunn, 139 N. Juniper St., Philadelphia, Pa., have a similar A.C. relay selling for about $6.00 (1936).

Although all the parts used were made by the writer, discarded industrial time recorders or time clocks might be converted to operate similarly to this one. Here a difficulty arises, however, in that none of them has a

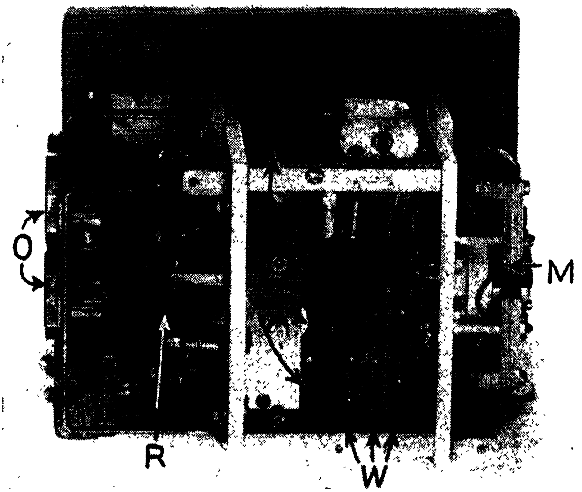


FIGURE 4
Top View.

seconds wheel and it is just about as difficult to rebuild an old machine as it is to make one in its entirety. A variety of linking mechanisms between the time wheels may be used, such as a ratchet and pawl system described above, direct gear connections as in ordinary clock movements, or the use of intermittent gears as in revolution counters. Also, each time wheel can be replaced by two smaller wheels, one for the units (0 through 9) and the other for tens (0 through 5). Increasing the number of time wheels adds to the problem of suitably linking them together.

The photographs show the recording timer as constructed, and go farther in describing it than could a whole volume of words. The entire unit is housed in a veneer-wood box, covered with imitation leather (Figure 5).

At the present time the writer is making a set of dies with which to die

cast the three numbered wheels in white metal. Ratchet, wheel and raised numbers will thus be cast in one piece. These wheels will be made available to anyone at a nominal cost. The synchronous clock motor used is of the self-starting variety and has a high starting and running torque. It is called the "Synchron Unit," and is made by the Hansen Mfg. Co., Princeton, Ind., selling for $1.85 plus postage (1936). The completed recording timer costs not over $10.00 for materials.—*2346 North 47th Street.*

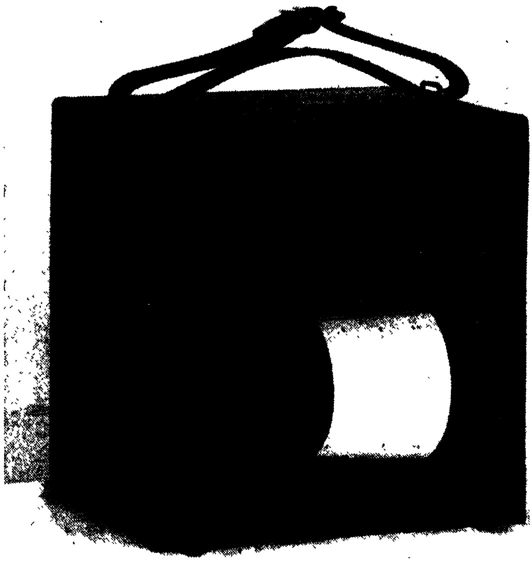


FIGURE 5

The completed recorder.

Meteor Photography

BY PETER M. MILLMAN
David Dunlap Observatory of the University of Toronto, Richmond Hill, Ontario

The amateur astronomer who possesses a good camera often wishes to know some way in which he can use it in the definite advancement of astronomical knowledge. A program of meteor photography provides the surest means by which valuable results may be obtained, while in no way duplicating the work done at the large observatories. Meteors being local phenomena in the earth's atmosphere, thousands of stations located all over the United States and Canada could simultaneously carry out a program of meteor photography, and the value of the work carried out at each station would actually increase with the number of stations similarly engaged. This is not true of any other branch of astronomical photography. When we add to this the fact that in meteor photography lenses of very modest aperture are the most efficient, and that an equatorial mounting and driving clock are not necessary, we see that it is really the ideal field for the enthusiastic amateur photographer. However, in general, meteor photography has been woefully neglected in the past, perhaps because it requires more perseverance than most other branches of astronomical study. It is impossible to secure meteor photographs at will, in the way we photograph other objects. Even assuming that we have the requisite instrumental equipment and a clear sky at the time of observation, the success or failure of the program depends to a great extent on luck. And yet it is this very element of chance that adds zest to the work, and when one does secure a really fine meteor photograph it occasions a thrill which is totally lacking in the more standardized branches of astronomical photography.

Let us consider the best type of lens to use in photographing the elusive meteor. In stellar photography we have point sources of light and the actual aperture of the lens, that is, its light gathering power, is of prime importance. In direct meteor photography we have a source which is effectively a line with no thickness. Here, as Öpik has shown (*Harvard Bulletin* 879, p. 5, 1930), it is the aperture ratio (ratio of focal length to aperture) which is the chief factor in determining the efficiency of the lens; approximately, the efficiency varies inversely as the square of the aperture ratio. The absorption and reflection of light by the glass of the lens, however, must be taken into account, and since one never knows where the next meteor will appear, the chance of photographing one varies directly with the area of the field covered by the lens. It is because of these last named considerations that the lens with the smallest aperture ratio is not always the most efficient for meteor photography. A highly corrected F 3.5 lens usually has a much greater total thickness of glass and a much smaller field in good focus than the corresponding F 4.5 lens. A lens for meteor work should have a field 30 or 40 degrees in diameter in really excellent focus. Lenses such as the Zeiss Tessar or Voigtlander Skopar, of aperture ratio F 4.5 and focal lengths ranging from 4″ to 10″, have been found excellently

suited to meteor photography. As in all astronomical work, permanence of the record and adaptability to accurate measurement are of the greatest importance and a plate camera is much to be preferred to one taking only roll-film.

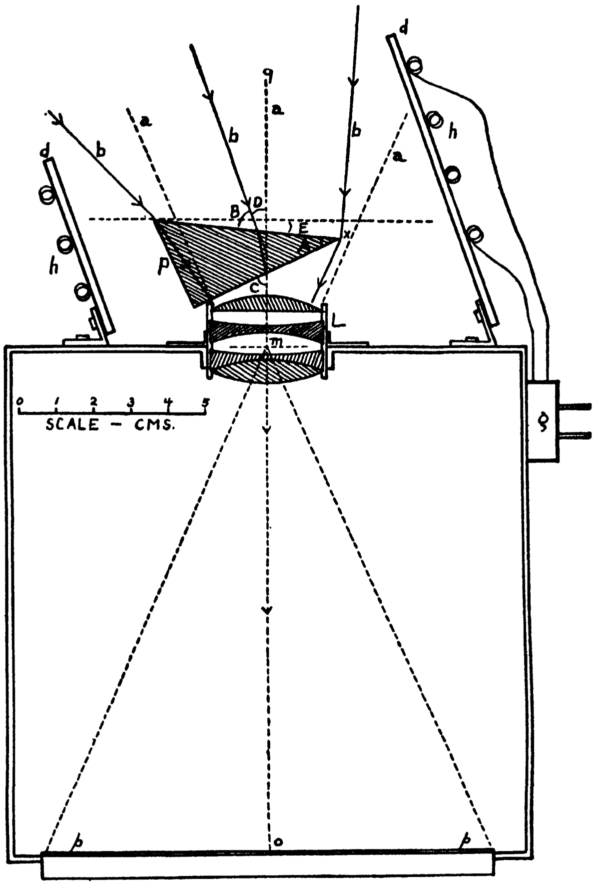
Focusing the camera is best done by trial and error. If there is an infinity mark on the camera, use this as an approximate focus; if not, then focus roughly on a distant object by means of a piece of ground glass. Successive exposures on the stars of from one to five minutes can now be made on a clear night, setting the focus at several positions on either side of the approximate point previously determined. If the camera is kept stationary the stars will trail, and by making the exposures of different lengths each will be identified and thus only one plate need be used. When this has been developed the exposure with the best focus can be determined. Sometimes it is wise to make a second focus test using a smaller range of settings on either side of the focus determined by the first test. A small eye lens giving a magnification of 6 to 10 diameters will be found necessary for examining the focus tests. The camera should now be fixed firmly at the position of best focus, ready for use on some night when a large number of meteors is expected. A tilting top, or a mounting by which the camera may be firmly held when turned to any part of the sky, is necessary for the best results. A meteor will generally photograph as a straight line of varying density and may lie at any angle on the plate. The stars will all appear as trails which approximate segments of circles centered at the north celestial pole. A guided plate will show the stars as dots and is of course much finer for show purposes, though the scientific value of the meteor photograph is not increased. There is no objection to mounting the meteor camera on an equatorial mounting provided that this is without vibration and a good driving clock is available. Guiding entirely by hand with slow motion is not recommended, as a slight irregularity in motion might occur just as a bright meteor crossed the field of the camera. This would introduce a spurious irregularity into the meteor path and render it useless for accurate reduction. With a perfectly dark sky, away from city lights and haze, and a lens of aperture ratio F 4.5, most types of plates may be exposed for an hour without showing too much sky fog. Near lights, or with a moon, the exposure time should be reduced to 30 minutes or even 15 or 10 minutes where the sky is very bright.

In the above I have been speaking only of the direct photography of meteors. The photography of meteor spectra is more difficult but proportionately of much greater value to astronomy. Up to the close of 1935 only 39 meteor spectra had been photographed and some of them are faint and show very little detail. (*Jour. R.A.S.C.*, Vol. 28, p. 279, 1934; Vol. 29, p. 241, 1935; Vol. 30, p. 249, 1936). Although meteor spectrophotography is by no means "simple and easy" in the accepted sense of the words, it presents no serious difficulties to the experienced photographer or to the telescope maker who has really used his instrument for an observational program. The small number of meteor spectra photographed to date is due chiefly

to the fact that, until fairly recently, scant attention has been paid this subject. The assistance which the amateur can render in this field is demonstrated when it is realized that nearly half the meteor spectra photographed in the last few years have been secured by amateurs. The Texas Observers of Ft. Worth have alone contributed seven. Meteor spectra are of great value not only in the study of the meteors themselves but in revealing atmospheric conditions at heights where meteors are visible, from 25 to 100 miles above the earth's surface.

What is the instrumental equipment necessary for meteor spectrophotography? In addition to a lens of the type used for direct photography one needs a prism of glass or quartz of high optical quality and somewhat larger than the lens. For best results the refracting angle should be about 30°. Small angles give too small a dispersion; and, while angles as large as 45° can be used, the glass absorption greatly cuts down the speed of the optical system. The prism is mounted firmly in front of the lens and as close to it as convenient (see Figure 1). The position should be one of minimum deviation, that is, the rays of light should pass symmetrically through the prism so that angle C equals angle B. The prism will be in the correct position if the front surface is set at an angle E to the plane of the plate or lens, where $E = (A - D)/2$, and the thin edge of the prism is nearest the lens when E is positive. A is the refracting angle of the prism; D, the angle of minimum deviation, may be found to the required degree of accuracy by setting the prism on edge on a large piece of white paper on which has been drawn a single straight line and then studying the way the light is bent by observing this line through the prism. The exact angle at which the prism is set, however, is not nearly so important as making sure that the prism is firmly mounted so that its position with respect to the lens will not vary in the slightest throughout the course of the observation. This last point cannot be too strongly stressed. The prism must be larger than the lens to include the entire pencil of light *a,a,a*. Since the thin side of the prism is very much more transparent than the other the position of maximum efficiency for any one prism will generally be found to be one where a small portion of the pencil *a,a,a* is not covered, as at *x* in the figure. To avoid troublesome direct images on the plate this space should be masked out, while care is taken not to cut off any light entering the prism.

At most stations in Massachusetts and Ontario, where the writer has carried out photographic programs, considerable trouble has been encountered with dew and frost which have an unpleasant habit of condensing on the prisms and lenses. To avoid disappointment the meteor photographer is strongly advised to equip his cameras with some type of heating arrangement. A very convenient form consists of coils of resistance wire wrapped around an insulated dew cap. At the Dunlap Observatory heaters consisting of 50 to 60 feet of Chromel C wire No. 25 are used. The wire is wound into a tight coil about an eighth of an inch in diameter and then this coil is stretched around the dew cap in a helical form. The total resistance



Drawing by the author

FIGURE 1

Diagram showing the arrangement of the essential parts of a meteor spectrograph utilizing an F 4.5 lens of 135 mm. focal length and a 30° prism. P, prism; L, lens; oq, optical axis of lens; om, focal length of lens; pp, photographic plate; dd, dew cap; hh, heating coils; g, electric plug for heating coils; aaa, pencil of rays which enters the lens when it is used without a prism; bbb, pencil of rays which enters the lens when it is used with prism.

of such a heater is 40 to 50 ohms and when one or two carbon lamps are placed in series with it it can be plugged into the standard 110-volt circuit. The resistance of the circuit should be adjusted so that the heater just feels slightly warm to the hand when the camera is in the laboratory. In the writer's experience no trouble at all with dew or frost has been encountered since these heaters were installed. If several cameras are used simultaneously the heaters can all be arranged in series and very little added resistance will be found necessary.

The adjustment of the focus for a meteor spectrograph is performed in the same way as for direct cameras, except that in this case the prism spreads the light into a spectrum, so that the star trails are not sharp, even when in focus. For this reason the focus must be judged by the sharpness of absorption lines in the stellar spectra. The Balmer series of hydrogen is the best for this purpose; Sirius in winter and Vega in summer are convenient stars to use since they are bright and show the hydrogen lines very strongly. It must be remembered that a prism disperses the light in a direction perpendicular to its thin edge. To obtain spectra of the highest quality the star should trail approximately at right angles to the dispersion, in other words, parallel to the thin edge of the prism. Similarly, when exposing for meteors, the camera should be turned so that the thin edge of the prism is parallel to the most probable direction of flight of the meteors. This is important since the spectrum of a meteor crossing the field exactly parallel to the dispersion cannot be photographed. It is also important to secure a few spectra of a star like Sirius when the camera has been finally adjusted. They will serve as dispersion standards and make possible the complete study of any meteor spectra photographed.

In spectrophotography, even more than in direct photography, the nominally fastest lenses are not always the best, for here good definition is absolutely essential or much spectral detail is lost. To photograph one meteor spectrum in good definition is far more important than to secure ten that are of only average quality. In the experience of the writer, lenses faster than F 4.5 do not have the requisite definition over a wide enough field for efficient meteor spectrum photography. The longer the focal length the greater the dispersion possible with a prism of given angle, but also the greater the glass absorption of both prism and lens. A practical range of dispersions for this work is from 0.5 to 1.5 mm from $H\beta$ to $H\gamma$. With an F 4.5 lens of 25 cm focal length the most efficient prism over the whole photographic range is one of ultra-violet crown (Jena glass number UV 3199), angle 30° to 40°. Almost as good in all but the short wave-lengths is a 20° to 30° prism of light flint (Jena glass number O 340 or O 602). To get sufficient dispersion with a lens of 13.5 cm focal length the light flint should be used, the prism angles ranging from 30 to 40°.

The specifications for a prism to be used in meteor photography are not quite as exacting as is the case for some prisms used in laboratory work. The chief requirement is that there be two plane surfaces of adequate size and high optical quality ($\lambda/8$ to $\lambda/10$, say) but the exact angle between

these two planes is of no consequence nor is the position of their line of intersection. Only two faces of the prism need be optically ground and polished, all the other surfaces being rough ground. Satisfactory prisms of such a character have been secured at reasonable rates from the firm C. P. Goerz, Am. Optical Co., 317 East 34th. St., New York City.

A question may arise here as to the possibilities of the new Schmidt cameras in the field of meteor photography. They may prove very useful in the direct photography of meteors because of their tremendously fast

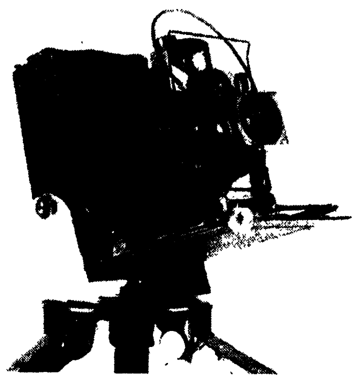


FIGURE 2

Meteor spectrograph, shown without dew cap and heater.

aperture ratios. They may not be particularly suited to meteor spectrophotography because, apart from the smaller field in good focus, there is another and greater difficulty. To secure adequate dispersion in a camera of 6″ focal length a prism of about 30° refracting angle is required. But a Schmidt camera of aperture ratio F 1.0 has an objective 6″ in diameter and a 30° prism large enough to cover this would have a prohibitive light absorption (and probably a prohibitive cost as well). The rate at which the prism size increases with the size of the objective is rather alarming. If the camera is made of very short focal length then the dispersion is too small to be useful.

The accompanying illustrations show the results that can be obtained with modest equipment. In Figure 2 is a meteor spectrograph with the heater and dew cap removed so that the position of the prism in front of the lens may be seen. The camera is a Voigtlander Avus with the F 4.5 Skopar lens of 135 mm focal length taking a plate 9 by 12cm in size. The prism is by Hilger, of silicate flint glass, with a refracting angle of 30°. The two meteor spectra reproduced in Figure 3 were photographed with this instrument and clearly indicate the fact that large and very expensive instruments are unnecessary in meteor photography. In each case the

meteor crossed the field of the camera almost perpendicular to the direction of the dispersion. It will be seen that the light of meteors is similar to that of a glowing gas, the spectrum consisting of many bright lines with little evidence of a continuous spectrum. The two spectra illustrated here represent the two chief types observed: Type Z, which contains in the main the atomic lines of iron, and Type Y, which exhibits in addition to the iron two very strong lines in the violet, the H and K lines of ionized calcium. Type Z in general seems to correspond to the lower meteors and probably represents the slower objects that penetrate below a height of 50 miles.

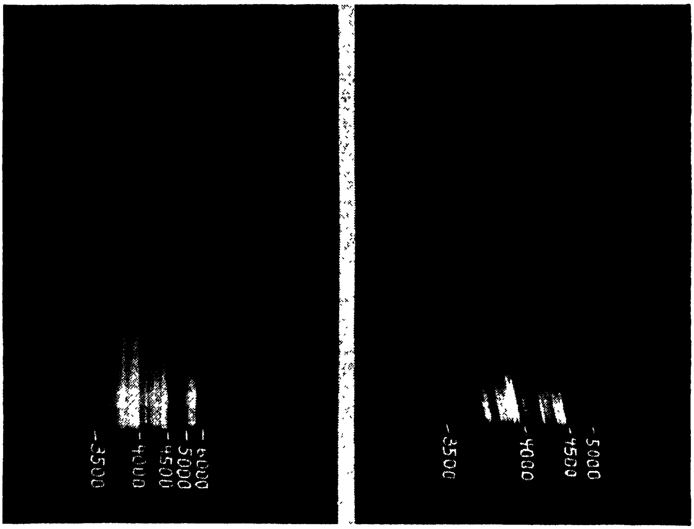


FIGURE 3

Typical meteor spectra. Left: Type Z—Nov. 18, 1935, Dunlap Observatory, Richmond Hill, Ont. A blue Leonid as bright as Venus. Taken on Ilford Meteor Pan plate. Wavelengths given in angstroms. Right: Type Y—Dec. 15, 1931, Blue Hill Observatory, Mass. Orange sporadic meteor of the brightness of Jupiter. Taken on Cramer Hi-Speed plate. Wavelengths given in angstroms.

(For a more complete discussion of meteor spectra see *Harvard Annals*, Vol. 82, pts. 6 and 7, 1932 and 1935).

A rotating shutter, driven by a synchronous motor, so mounted that it completely covers the lens 10 to 30 times a second, is a valuable accessory. The resultant meteor trail will thus be broken up into segments, and not only the angular velocity of the meteor can then be computed but the segmented trail will indicate the ratio of the instantaneous luminosity at any one point to that of the enduring train, or else it will demonstrate that

the latter was not strong enough to impress itself on the plate. A meteor spectrograph equipped with a rotating shutter will reveal the nature of the spectrum of the persistent train where this has an intensity great enough to show on the photograph. (*Jour. R.A.S.C.*, Vol. 30, p. 101, 1936).

The choice of plates for both kinds of meteor photography is of extreme importance. In direct photography we have a single image, and the entire sensitivity of the plate is applied to building up the intensity of this one image. A fast panchromatic plate is usually the most satisfactory, as it is sensitive over a wide range of wave-lengths which materially increases the speed, especially as many meteors are of a decided yellow or orange color. In spectrophotography we have a large number of images corresponding to a single meteor, each image representing a different color or wave-length; it is the maximum sensitivity of the plate in each of several colors that we are interested in, and no one type of plate is fastest in all regions of the spectrum. For example, the Cramer Hi-Speed plate is extremely fast in the blue region and well suited for spectrophotography in the range $\lambda3800$–$\lambda4800$, but it not generally so fast as a good panchromatic plate for direct photography. The Cramer Iso-Presto has almost the same blue sensitivity plus a band in the yellow-green but it is not as clean working as the Hi-Speed and gives considerably more sky fog. The Ilford Astra II plate is another very good ortho plate with high blue sensitivity. To the writer's knowledge the first attempt to specially sensitize plates for meteor work was made by the Ilford Company at the request of Mr. J. D. Williams, then of Tucson, Arizona. The result was a specially sensitized Hypersensitive Panchromatic plate which proved to be very fast when tested but seemed to have unreliable keeping qualities. This plate was later developed into the Ilford Meteor Panchromatic plate which has now been renamed Astra IX. The writer uses the Astra IX regularly for meteor spectrophotography. It is characterized by a high speed emulsion with relatively fine grain and a very even gradation of sensitivity through the blue and visual regions, a maximum at about $\lambda6000$ and a sensitivity down to about $\lambda6500$ for good exposures. Though more satisfactory as regards keeping qualities than the earlier emulsions it is advisable not to store the Astra IX too long and, like all panchromatic plates, it probably keeps better in a refrigerator. The Ilford Hypersensitive Panchromatic plate is another very fast emulsion, especially suitable for direct photography. Successful photography of meteor spectra in the red has also been carried out with the Eastman I C Special Spectroscopic plate. This carries a little farther into the red than the Astra IX but has a much lower sensitivity in the green and in general has been found to have rather large grain. The Eastman Super-sensitive Panchromatic emulsion is very suitable for the direct photography of meteors, as is the Imperial Eclipse Ortho soft plate. The above remarks are meant to serve only as a rough guide in the selection of plates. It is impossible to give a final word on the matter, and anyone taking up meteor photography seriously is advised to test frequently various emulsions against each other by making, in rapid succession, uniform ex-

posures of 5 or 10 minutes. A determination of the faintest star trails photographed for any given declination will then give a good indication of the relative speeds of the plates when used under actual observing conditions.

We should next consider where to direct the cameras for meteor observation. The writer has investigated this question in some detail (*Proceedings, National Academy of Sciences,* Vol. 19, p. 34, 1933), and it appears that for sporadic meteors almost any region of the sky with an altitude greater than 30° is equally good, with possibly a slight advantage at altitude of around 45° for spectrophotography. The most likely direction of flight for sporadic meteors is downward, so that the prism should always be set with the thin edge vertical. In the case of observations made at the time of showers with known radiants, the region near the radiant is much the most favorable for photography, in spite of the fact that casual observations would lead one to think that the brightest meteors appear at some distance from the radiant. It is the slow angular velocity near the radiant that makes this region richer in meteors that can be photographed. Very often a bright meteor far from the radiant appears conspicuous to the eye, which automatically follows its swift flight, while a fainter but slower meteor near the radiant would have a greater photographic effect. When the radiant is not far from one horizon, the sky near the opposite horizon is a good direction in which to point any extra cameras, after the fields within 30° of the radiant have been covered. Of course the above rules apply only to average conditions and an even distribution of meteors in space; local irregularities on any one night may greatly change the actual distribution.

The meteor photographer should make every effort to plan visual observations in conjunction with the photographic program. This is especially necessary where stationary mounts for the cameras are used, as in this case the visual record of the time of appearance of the meteor is the only means by which the exact path among the stars can be calculated from the photographic plate. The stars trail across the plate during the exposure and they form a complete frame of reference only when it is known at what time during the exposure the meteor appeared. For the same reason it is necessary to record accurately the exact times between which the plate was exposed. By covering the lens for 5 to 20 seconds one minute from the beginning and end of the exposure, small breaks in the star trails are made which are more accurate reference points than the ends of the trails.

If it is desirable to eliminate visual observation in a long systematic program of meteor photography the information derived from the photographic plate alone must be clearly understood. We will assume that in all cases the time of the beginning and end of the exposure is accurately recorded and that the latitude and longitude of the observing station are known. A meteor photograph secured with a stationary camera will define accurately the altitude and azimuth of the meteor but will leave its right ascension uncertain within definite limits depending on the length of the exposure. A guided plate will, on the other hand, accurately define

the right ascension and declination of the meteor, while leaving its altitude and azimuth uncertain within limits. If two cameras are directed to the same field, one being stationary while the other is guided, then the time of appearance of the meteor may be determined and its position accurately computed both with respect to the equatorial and the horizontal system of coordinates. Similarly, in a program of height determination, where two cameras are used at either end of a suitable base line, (preferably 10 to 30 miles in length), if the cameras are both stationary, then the exact path of the meteor in our atmosphere can be computed but its astronomical radiant is uncertain; if both cameras are guided the astronomical radiant is defined but the height of the meteor is not definitely known. If, however, there is a marked point on the meteor trail, such as a burst, and one camera is guided while the other is kept stationary, the radiant of the meteor and its height above the earth's surface can both be determined. Even if the meteor trail does not exhibit a marked burst the point of maximum intensity on the trail can be used, but it may be necessary in this case to make a small correction to allow for the fact that the meteor is approaching one station more rapidly than the other.

Setting up a camera and hoping that a bright meteor will cross the field covered by the lens seems a very haphazard method of conducting a scientific program, yet it is the most practical one. It has been suggested by several that a more logical method would be to have the camera mounted on a very flexible mounting so that it could be instantly directed towards a bright meteor. While such a procedure might be successful in particular cases, in general the practical difficulties would be very great. Meteors rarely remain visible for longer than a second or two. There is no guarantee that an observer would see a meteor as soon as it becomes visible, as a very large area of the sky would have to be covered to gain any real advantage over the stationary camera. Covering this large area would also necessitate swinging the camera through long arcs. For a meteor photograph to be of definite scientific value the camera would have to be brought to a dead stop and rendered vibrationless before the shutter could be opened. In most cases the meteor would have disappeared by this time. After even two or three fruitless attempts to photograph a meteor in this way the plate would have to be changed to avoid becoming confused with the various sets of star images. The amount of photographic material consumed would thus be several times as great as if the camera were kept stationary, and the method would almost undoubtedly prove less efficient. During the Leonid observations of 1931 the writer did have a spectrograph so mounted that it was swung away from the radiant by a small motor at the average angular velocity for the Leonids in the region of the sky covered by the lens. At the end of a swing of 30° to 40° it was quickly brought back again and the swing repeated, this see-saw motion being kept up all night. It was hoped that this would reduce the effective angular velocity of the Leonids and enable fainter meteors to be photographed. No results were obtained with this camera in 1931, though the method did not have a fair trial owing to

cloudy weather. More recently Professor Whitney in California has successfully photographed a meteor spectrum with equipment arranged in a somewhat similar way (*Pub. A.S.P.*, Vol. 46, p. 279, 1934). In this latter case four spectrographs were kept in continual rotation about an axis perpendicular to the direction to the Perseid radiant. Strangely enough, the meteor photographed was not a Perseid but a sporadic meteor.

The number of meteor photographs secured in a short program of observation is chiefly a matter of luck. As a rule any meteor as bright as Jupiter, or brighter, can be photographed with both direct and spectrographic cameras. Fainter meteors sometimes leave an image, particularly if they are of very low angular velocity. When the results of many photographic programs are averaged up, the number of hours exposed per meteor photographed becomes more consistent. A discussion of programs of meteor photography has been given recently in the *Jour. R.A.S.C.*, Vol. 30, p. 193, 1936, and the following table is taken from this summary. The observations of specific showers refer to those made on the three or four nights nearest the maximum date. The cameras used had lenses of speeds from F 4.5 to F 3.5 or faster and covered on the average 1200 square degrees of sky.

SUMMARY OF PROGRAMS OF METEOR PHOTOGRAPHY

	Hours Exposed	Meteors Photographed	Hrs. Exp. per Met. Photog.
Direct Photography			
Leonids (1929–1935)	120	26	4.5
Perseids (1931–1935)	50	14	3.5
Geminids (1933)	12	3	4.
General Programs (including shower nights)	599.	29	20.
Spectrophotography			
Leonids (1931–1935)	219	11	20.
Perseids (1934–1935)	81	4	20.
Geminids (1931–1934)	119	3	40.
General Programs (not including showers)	1351	5	270.

It will be seen that one direct photograph was secured for each four hours of exposure time during the Leonid, Perseid, and Geminid showers, and one for about 20 hours' exposure on the general programs. The total number of hours exposed per meteor photographed is about five times as great for spectrophotography. These results may be taken as guides for future work but it must be remembered that the Leonid programs reported above covered the last Leonid return and that these meteors will be much fewer in number during the next 25 years.

The periods of the year during which meteor photography is likely to prove fruitful are listed below. Of these the Perseids and the Geminids are the best showers for photography.

Quadrantids	Jan. 1–3	Perseids	Aug. 10–14
Lyrids	Apr. 20–22	Orionids	Oct. 18–20
Eta Aquarids	May 3–5	Leonids	Nov. 15–18
Delta Aquarids	July 27–29	Geminids	Dec. 10–14

Unless the amateur is prepared to lay out a good deal of money in buying photographic supplies it is hardly worth his while attempting to photograph sporadic meteors between the dates of the showers given above. It is well worth while, however, to photograph during the shower nights when a larger number of meteors than usual is to be expected.

In closing, it should be added that meteor photography is at all times a sporting proposition and there are bound to be disappointments. It requires great patience and an ability to keep on in spite of initial failures, but if one tries hard enough and often enough, success is sure to come. To offset the disadvantage of uncertainty in meteor photography there is the knowledge that a chance bright fireball in just the right position may enable one to secure the best meteor photograph yet obtained.

The writer is located at the Dunlap Observatory, Richmond Hill, Ontario, and is always glad to answer questions or to offer what advice he can to anyone interested in meteor photography.

Drawing by Russell W. Porter

What's a mere telescope, between friends?

Stellar Photography

By William S. von Arx
Brooklyn, N. Y.

Stellar photographers are members of a lonely cult. English amateurs seem to lead the world in this field, and even have a section of the British Astronomical Association devoted to it. For those who enjoy doing work with extreme accuracy, and doing their own instrument making, this is a thoroughly interesting field. It is, of course, possible to buy the necessary mechanisms, but that takes away half of the fun, as well as the major portion of one's savings. The initial requirement is a good mounting, of staunch con-

Figure 1

A crude hand-driven mounting for the beginner. Brownie 2A Kodak and pocket spy glass as finder.

struction and mechanical refinement. After this, the trouble starts, for a nearly perfect driving mechanism must be built. This is the nemesis of most experimenters, and must be planned beforehand and executed with great care; otherwise the whole project will try or destroy one's patience.

However, assuming that this has been accomplished, the next job is to find a suitable lens for star work. This may require much hunting in second-hand stores and lens shops; or you may happen to find a lens almost immediately. It is best to do your trying of lenses "on memorandum," otherwise

you are likely to waste money on lenses that you can't resell. When you find the right lens, mount it, focus it, and you are ready to start work.

The first photograph taken will give a big thrill, even if the images do trail all over the plate. Experience has shown, however, that to get an idea beforehand of what you are doing, it is best to build a crude mounting of some sort (Figure 1) and literally try your hand at guiding, not using a clock or any sort of help other than a manual slow motion in right ascension.

FIGURE 2

Milky Way in Cygnus. North America nebula to left of bright star, Deneb. Taken by Charles W. Elmer with an 8¼" focus lens working at f/3.5. 2½ hour exposure.

When you succeed in getting round images by driving a lens of 12" focus in this manner, you will be sufficiently skilled to attempt work of a higher type. A two-hour exposure on the Milky Way, in Cygnus will show the delicate tracery of the famous Veil Nebula, the North American Nebula, a host of stars and diffused nebulosity that is inconceivable to the ordinary telescopist (as in Figure 2). The Hercules Cluster is an easy mark for lenses of 18" focus and moderate aperture. It is best, however, not to anticipate too much, or else disappointment will be the result of your first endeavor.

The Mounting: The equatorial mounting is the only type permissible in astro-photography, except for making instantaneous exposures or in the photography of meteors. The reason for this is that the stars must be followed by the camera in their diurnal motion. They will trail across the plate if an exposure of more than a second or two is attempted without following their motion. The most common type of mounting suitable for this work is the German type, but this has the disadvantage of being incapable of crossing the meridian in the case of fields north of the zenith. A modification of this type has been designed for astro-photographic use. This is the composite type, similar to that of the 72″ telescope at the Dominion Astrophysical Observatory. All parts of the sky can be reached with the flexure remaining constant, hence the possible error due to this cause is reduced to a minimum. The question of flexure is of great importance in astro-photography, for so many errors creep in, due to unavoidable circumstances, that the elimination of those that are avoidable is a great help. Another mounting which is used frequently is the English fork type, which has the advantage of being very compact, but the disadvantage of having a tendency toward undue flexure unless very heavily built. A big point in its favor is its freedom from counterweights. There are, of course, a great many other designs, but the ones named are by far the most practical for the work in view.

The composite mounting, being of closest kin to the conventional German type, will be discussed first. In essence it is the German equatorial, with its polar axis extended northward to a second supporting pier, which adds to its stability. The worm and driving mechanism is located at the south end of the polar axis, so that it will not interfere with the view of the northern sky. Midway up this axis the main bearing for the declination axis is placed, at right angles to the polar axis—the camera on one side and a counterweight on the other. Setting circles, verniers and clamps are assembled exactly as they are in the German design.

The immediate questions are: how to build it, how strong must it be, and if this composite type is used, how big must it be, *and can it be driven?* Much of this is up to you, but always remember that it is very difficult to over-build an instrument of this sort. It is far better to make a heavy but efficient mounting than a beautiful piece of lathe work that wobbles in the slightest breeze.

For mountings of the size in which most of us are interested, the polar axis may be made of a well-seasoned piece of hard wood, preferably oak, turned to a sturdy taper. Square stock, the width of which is at least one eighth the length, is turned on a lathe so that the ends will fit the inside diameter of a set of ball bearings, and tapered from either end toward the point at which the declination axis will be placed, but left square for a space equal to the width of the cameras to be used. Provision must also be made for the worm wheel on the south end of the axis, by interrupting the taper with a parallel spot at a place where the hub of the wheel will fit snugly. At the point where the declination axis is to pass through, a hole may be drilled to accommodate the bearings. These should be 1″ cone bearings,

which may be purchased cheaply from any auto wrecker. They should fit tightly, with their apices toward one another. The shaft running through these bearings should be equipped with a plate on one end, to which the camera may be screwed. A pair of lock nuts on the opposite side of the bar will hold the camera plate close to the bearings, as well as vary their freedom of motion of the bearings. The shaft may be coarse-threaded, to hold lead disks used as counterweights, and these are adjustable by simply screwing them back and forth. A large friction disk of metal should be fitted to the camera side of the axis, immediately below the camera plate. This acts as a damper for the declination axis, and it may also be graduated in degrees and used as a declination circle, with the indicator fastened to the polar axis. An R. A. circle may be similarly engraved on the worm wheel, in quarter hours.

If you don't happen to be fortunate enough to have the use of a machine lathe to make the worm wheel in R. A., you may buy an 8″ spur gear with 288 teeth from the Boston Gear Works (North Quincy, Mass.) for less than $4.00 (1935). This, when fitted with a suitable worm, will act quite well enough. The hole will probably have to be drilled to a large diameter. If the polar axis will not permit the worm gear to fit and still meet the size of the south bearing, continue the shaft through the bearing and fit the gear on the other side. It will function the same.

A vernier in declination is not as necessary as it may seem, because most mountings, once set in accurate polar adjustment, require little change in declination near the zenith, where most of the work is done. The friction disk, if properly fitted, should permit small adjustments by a slight pressure of the hand. A clamp is necessary, however, to prevent accidental moving of the camera. This may be fashioned from a thumb-screw of considerable size, threading into the polar axis just outside the periphery of the friction disk. With this arrangement, the disk is held against the axis by simply tightening the screw. Thus the cameras are firmly clamped.

When the main bearings are finally put on and supported on two stout wood or concrete piers at the proper altitude and azimuth, the entire mounting should be given a coat of stone gray paint. This color is the most practical because it doesn't have a high albedo, yet it reflects enough light to be seen at night. This helps greatly in finding the eyepiece of the guide telescope, and in avoiding collision with any part of the instrument.

This covers the composite mounting, in a very general way. A mounting of this sort, with a 30″ or 40″ polar axis, will carry cameras up to 20″ to 24″ focus. This is plenty big enough for the pocketbooks of amateurs of my acquaintance.

I prefer the English fork mounting (Figure 3, at left) to all others used in astrography, because of its simplicity of construction and use. No delicate counterweighting systems are needed, and all the weight is concentrated in the base, which is supported by a single pier. It also adapts itself nicely to a roll-off roof shelter.

The moving parts of this mounting can be made entirely of metal, with

very little expense. To start with, a pair of main bearings from an old auto crankshaft will do to hold the polar axis, which is of cold-rolled steel. The longer this axis is made, the less the inaccuracies of the bearings will show up (20″ is ample). One end of this rod should be machined to receive a bolt that fits the shaft diameter of the 8″ spur gear mentioned in the outline of the composite mounting. This is very close to ½″. Then a fork of heavy strap iron or steel (2½″ x ½″) is forged into a sharp-cornered

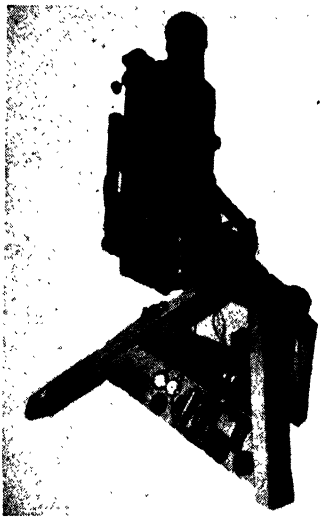


FIGURE 3

Left: Type of mounting used by the author. The finder, as well as the telephoto-camera and a photometric telescope, is mounted on the box-like camera. The gadgetry below is an assemblage of useful equipment, such as objective prisms, filters, micrometer eyepieces, polariscopes and other odd trinkets. A Zollner spectroscope is included, for the satisfaction of seeing spectra. Right: An impulse driven mounting. A family heirloom provides the time interval.

"U" shape and drilled to receive the bolt at the bottom. Make sure that, when lying on its side, the curve given the iron will not interfere with the action of the worm. While you are drilling the hole in the fork, the holes for the declination axis might just as well be made, if you have determined what their size shall be. These, if done nicely, will serve as bearings for the camera trunions. They should be at least ½″ x 3″ bolts, fixed through the camera walls, with the heads on the inside and nuts and washers on the outside, between the camera and the tine of the fork. These will project through the tine quite a distance, and a duplicate of the main worm gear may be bolted on and a worm set on the tine to actuate it as a vernier

in declination. This is necessary on this type of mounting, because of flexure when it is turned on its side. After the fork is bolted through the main worm gear to the machined end of the polar axis, the bearings are put on and the entire mounting bolted with iron straps to a strong wooden or concrete base. As in the composite mounting, the gears in declination and R. A. may be graduated and used as setting circles.

No effort has been made in this brief sketch to give detailed plans for construction of these mountings, the sole purpose being to suggest the idea and let the maker figure out his own problem, instead of following plans already laid out. In this way every one gets a different angle on the problem and new ideas are evolved.

The Driving Mechanism: The purpose of the driving mechanism is to keep the camera pointed exactly at a certain part of the sky during the entire exposure. There are two types of driving machines, the continuous and the intermittent or impulse drive. The latter is the more simple, as far as equipment goes and in the construction of the drive. Figure 3, at right, is of this type.

The mainstay of the impulse drive is the pendulum, which, when swinging, beats off accurate intervals of time. By gearing the worm of the mounting down to a ratio of about 1,440 to 1, a rachet gear with 60 teeth, moved ahead one tooth per second, will give the required speed of rotation to the mounting. A gear box of brass, and gears from a substantial clock movement, may be used in conjunction with the worm, to give the required reduction in speed, and the ratchet attached to that.

The pendulum has a platinum wire attached to the tip, which dips into a globule of mercury each time it swings, and thus it makes an electrical contact or impulse. The pendulum may be grounded on the frame of the escapement, and another wire attached to a metal receptacle for the globule of mercury. This, when put in a series with a battery, will make impulses which, when led to a pair of electro-magnets with an armature, will be converted into mechanical motion. This in turn is transferred to the ratchet by means of a push rod. Thus, if the pendulum is adjusted to the proper interval or beat, the ratchet will move the mounting at the proper speed to keep step with the stars. The motion is jerky, to be sure, but when you stop to figure the angular motion of the earth during one second you will see that the jerking motion has little effect. A one second beat is sufficient to use on a camera of short focus, but when foci of 12″ or more are used, the impulses must be more frequent, otherwise elongated images will result. Of course the gear ratio must then be increased to take care of the increased frequency. You may find that a relay will have to be used in the circuit, because the mercury oxidizes too quickly when more than 20 volts are used (keep the amperage as low as possible). The purpose of the platinum wire is to keep the oxidation at a minimum. A strip of brass, with a ball-pene hammer dent in one end, will serve well to hold the mercury in a nice little globule, so that the resistance against the pendulum will be minimized.

When the proper clock rate has been found by adjusting the length of the pendulum you will find that, even then, the instrument does not follow the stars exactly, because of atmospheric refrangencies due to currents in the upper air. These may be corrected by placing a switch in shunt across the pendulum and the mercury cup. If this switch is connected with a long enough cable, it may be held in the hand of the observer while working. (A flash light case makes a neat job, as shown hanging to the right in Figure 3, right). By chattering this switch, more impulses per second will be made, hence the mounting will be sent ahead of the usual rate; or by closing the switch, the circuit will stay closed instead of being broken by the clock, and the mounting will be held back. With a little practice one or more beats can be inserted or omitted, as the case may require, thus correcting any small errors in R. A.

Other means of driving may be used, but from my own experience this method is best suited to the needs and pocketbooks of most amateurs; all that is needed being a pendulum clock, an electric bell or telegraph sounder, some odd gears and a battery.

However, if a continuous drive is wanted, there are several ways to go about it: first, by means of the synchronous motor which requires a great deal of gear reduction and laborious tinkering; secondly, by means of a disk motor with a frictional governor. Both of these drives are quite practical, and with a little experiment in design they will have ample power to carry instruments of quite large dimensions.

In the case of the synchronous motor there is little to be said, except that gearing in the reduction of speed must be done with great accuracy, so that the telescope will be driven completely around in R. A. once every 23h 56m and a few seconds. The differing interval from the mean solar day will show up glaringly in a single hour of exposure; whereas in the case of the frictional governor on the disk motors (used in electric Victrolas) these small differences may be eliminated by incorporating a vernier adjustment on the speed control of the governor. This is a great advantage, in some ways, because at times a decided slowing of the rate of the mounting is required—as in the case of obtaining spectra with an objective prism, which will be discussed later. In either case, however, an ordinary belt drive somewhere in the set-up is advisable, in order that small changes may be made without stopping the motors. With such a drive the back-lash of the gears can be eliminated entirely by grasping the belt when the rate is too fast, or urging it ahead when the rate is too slow. Small changes can be corrected by this method which would be impossible by stopping the motor momentarily. Slippage of the belt is very slight and can be corrected in greater part by means of a tension wheel on it, or by a spring properly installed so as to keep constant the slippage which there may be. Any constant errors can be eliminated by adjusting the rate of the motor.

The initial demand of all these drives is, in any case, to secure smooth action unaffected by weather conditions. Extreme heat and cold change the rate of the governors on the disk motors to quite an extent. This can be

eliminated by using either alloys with low coefficients of expansion or a thermostat in a covering or chamber of asbestos; the heat for the chamber coming from an ordinary electric light bulb or from a resistor of about 1000 ohms. This is not as serious in actual practice as it may sound, because the weather changes are usually slow and quite constant over a period of hours.

Driving clocks are to most amateurs the most interesting part of the mechanism, because this part is the most exacting. Time should not be

FIGURE 4

A simple mounting driven by an old alarm clock movement. The polar axis is the axle of the front wheel of a bicycle.

considered wasted when it goes into the improvement of the clock, slight though the improvement may be. For every improvement, just that much less vigilance is required at the eyepiece of the guide telescope while exposures are in progress.

The ordinary alarm clock is not an altogether slovenly drive medium. Figure 4 shows a small mounting driven by a clock of this type, with the alarm mechanism removed. The gear which is directly attached to the main spring of the clock is meshed with a gear of the same pitch but of a diameter four and a fraction times its size. (It was found by experiment that the

spring gear turned a little over four revolutions per day: hence the ratio). There is a weight of a pound or so, suspended by a tangent strap to the larger gear, in order to take up back-lash and incidentally relieve somewhat the strain on the clock. The clock is held close to the larger gear by a light spring. Thus the R. A. of the camera can be changed merely by pulling the clock away momentarily.

This simple instrument proved quite effective on the Milky Way. The lens in the camera is one of the projection type, stopped down to about $f/3.8$ (focus $5\frac{3}{4}''$).

The Camera and Guide Telescope: The cameras used in this type of work are not at all conventional, for they are focused for infinity alone; and, once set, they remain set for the duration of their useful life. They are usually simple boxes of wood or metal, with a lens at one end and a plate holder at the other.

The lens, being the important part of the camera, must be of high optical quality; that is, an anastigmat, working at $f/5.6$ or better, having a hard focus, and a large flat field. To obtain all this data about a lens it is simply put into an improvised camera and used to take a picture. Focus it carefully on a distant landscape and wait for nightfall. When it is dark, prop the camera on a firm support and direct it at the equatorial stars. Expose for 20 minutes or so, and develop the plate. The images of the stars will be streaks running across the plate. To arrive at the decision, examine these with a strong magnifying glass. If the lens is suitable, these streaks will be solid black lines. If they are black lines on a lighter gray background band, the lens is undercorrected and therefore unfit for precise work. If they are excessively wide, try focusing the lens better, by moving it definite amounts, exposing a short time between changes, marking and numbering each change. Then develop the plate and choose the finest line, note its number, and return the lens to this point. (This method is one of the best to use in focusing cameras of this type). The size of the plate which the lens will cover can be determined from these tests by noting the points or region at which the definition of the images fall off. Use a plate that just includes this region, and you will be getting the maximum results in field which that lens will give. Some lenses have curved fields, and are in focus only when the plate is tangent to the field. These are practically useless for the work cut out for them here. Then, too, some lenses have properties that make round images an impossibility, even with perfect driving. These lenses are the type with striae, etc., in them. These give triangles, arrows, birds, crescents, etc., as images of points. These are obviously unsuited to the purpose, unless an unusual effect is wanted. These pretty designs are easily made with poor guiding.

There are some old portrait lenses on the market that work at $f/3.5$ or better, which can be bought cheaply; but beware of soft focus. Barnard used stopped-down projection lenses for some of his work; in fact, he advises their use in cometary photography. The modern anastigmat is the best for all-round work. However, try anything you can lay your hands on, as

some old lenses have remarkable properties. For example, some of the old rapid rectilinear lenses by Bausch and Lomb are excellent but very slow ($f/8$).

When you have selected a lens, build a box of well-seasoned wood, of sufficient weight to be quite rigid. The heavier the lens the more rigid this box will have to be, in order to obviate flexure, which is ruinous to good images. It is best to build the box around the plate holder, and a little longer

FIGURE 5

The Orion Nebula, taken with the telephoto camera working at f/25. Exposure 2 hours, Hyper Pan plate.

than the focus of the lens. A front, with the lens in it, should fit closely in the box, and slide back and forth with not too much freedom. When the lens is thus mounted, it may be focused in the way previously mentioned, squared on, nailed into position and the inside of the box painted a dead black.

After the camera has been made, a guide telescope must be found. This telescope should have a focus longer than that of the camera; in fact, the longer the better. And, too, the aperture should be as large as can be found, because bright stars are not always near the field to be photographed. The

quality of the glass need not be high, as it is used only as a finder and guide, to keep the images round. Any old thing with a good light grasp and sufficiently long focus will do. When one of these is procured, remove the eyepiece and unscrew the eye lens. In the barrel you will find a diaphragm. On this, two fine glass threads should be glued, at right angles to each other. These threads may be made by heating a glass tube over a bunsen burner until it becomes red hot, then pulling the tube out into a long thread. Probably this will be a failure at the first attempt, but a little practice will enable you to pull threads about .02″ in diameter, which is about the correct size. Choose the pieces nearest the center, because they are the finest, and cut them by breaking them with the thumb and a pair of tweezers. After gluing and drying, replace the eye lens and look through the eyepiece. You will see a pair of lines, perpendicular to each other, projected on the background of light entering the field lens. Replace the eyepiece in the telescope and focus it on a distant object. These cross lines will appear projected on the object.

This telescope must be fastened very rigidly beside the camera and as nearly parallel to it as possible, with a couple of loops of strap iron with alining pins screwed to the box. Then bolt the camera and its finder to the mounting, as its construction requires, and you are ready to take pictures.

Polar Adjustment: Every equatorial mounting, in order to work correctly, must have its polar axis brought exactly parallel to the axis of the earth. This must be done with great accuracy, otherwise the star images will trail, no matter how well the clock is rated.

There are several complicated ways of doing this, both by photographic and visual means, but there is a simple way that can be carried out in a few hours. Select three stars of very nearly equal declination, that are all above the horizon at one time and separated by about three hours each. Three good ones are: Beta Cygni at plus 27°48′, Mu Herculis at plus 27°45′, and Epsilon Bootis at plus 27°20′. There are many other sets, to be found by looking in a star atlas or the Ephemeris. Set the cross-hairs of the guide telescope on one of the three and, swinging in R.A., get the other two stars to fall on the lines as it is swung toward them. If they do not do this, change the position of the polar axis in the required direction until all three are in line, allowing for their respective differences in declination by accurate approximation. Do this with two or three sets of stars, until you are sure that it will work in every case. Then rate the clock by setting the guide telescope on a bright star, throwing the image out of focus and bisecting it with the cross-hairs. Watch the image, carefully adjusting the rate of the clock until it follows perfectly or nearly so. Now try your luck with a plate in the camera, exposing for 20 minutes. *Be sure that you keep the out-of-focus disk of the guide star carefully bisected on the wires during the entire exposure,* otherwise the images will trail. Develop the plate and see how good you are. If the images are round you are to be congratulated, for it takes considerable skill to control an instrument accurately enough for this.

If, in setting the mounting roughly at first by sighting at Polaris, a line is drawn from Zeta Ursae Majoris through Polaris, and retraced $1\frac{1}{4}°$, the true pole can be found much more exactly and much time saved. The distance between the pointer stars in the bowl of the Dipper is 5°; so, by mentally judging the required angle, carrying it over to the pole star and sighting the axis at this imaginary point, you will find that you are not far off when you make the test. It will perhaps make the situation a little clearer to say that the purpose of setting the mounting is to have the lines it describes across the sky for a definite parallel of declination coincide exactly with the actual line in the celestial vault. This perhaps explains the reason for choosing three stars of equal declination. If the stars are close enough to the chosen parallel they will determine a plane whose axis is coincident with that of the earth. Two stars would not be sufficient, because two points do not determine a plane.

Using the Instrument and Guiding: When you have gone through the preliminary work of building the instrument, the real fun begins as you use the instrument and discover its capabilities. To do good work is to guide well; in fact, it has been said that everything must be sacrificed to good driving. Practice is the only way to learn to do this, and patience is the password. Learn your instrument thoroughly, and be able to correct every little error on an instant's notice. Get used to the *feel* of each slow motion, the direction in which it must be turned to correct each error, and the amount of play that must be overcome before the adjustment takes hold.

Once the cross-hairs are set on a star, the guide telescope must not be touched, since even the slightest change will disturb the relative arrangement of the star's image on the plate and on the cross-hairs. It is also inadvisable to use a diagonal prism in the telescope, because these are particularly easy to knock out of position. When you get the mounting and clock adjusted precisely enough so that the instrument will follow for ten minutes or more without correction, long exposures may be attempted with fair certainty of obtaining good results.

However, there are many more things to do and think about than driving.

One of the worst enemies of the photographic lens is dew. This forms at the slightest provocation, and sometimes causes great consternation on the part of the observer. When dew forms on a lens it renders it practically opaque, as far as image forming properties are concerned. The main difficulty is in detecting its presence. Often there are no signs of dew in the night, and the observer goes on exposing. Meanwhile the dew has formed without his knowledge, and cuts off the light as effectively as a shutter. When the plate is developed, this watcher of the sky becomes irate, because he finds that, instead of his anticipated 15th magnitude stars, he has the bare outline of the constellation; and, too, he has been following with the greatest care for hours, when the plate has actually been exposed for not more than a few minutes. One may avoid this catastrophe by closing the camera periodically and inspecting the lens. If there is dew on it, don't call things square by wiping off the lens, for this only threatens the surface of the glass with

possible scratching; and, more than this, it lays a perfect bed for the next coat of dew to form. The best way to get around this difficulty is to place a 1000-ohm resistor in a hood over the lens, and switch it on when occasion demands. These resistors become hot enough to cause the air around the lens to become warmer than the dew point of the night, and thus they entirely obviate dewing. Don't worry about convection currents caused by this source of heat, for they will not interfere in the slightest. Simply place a generous hood around the lens, making sure that this hood doesn't interfere with the field of the camera, and mount this little heater in it. The larger the hood the better, because on windy nights that little heater will be put to the test. Windy nights are not too good for photography, but often the hard-working amateur has no choice in the matter.

When the more fortunately located observer in the open country finds himself in the midst of one of the velvety black nights that sometimes come, he often curses at least a part of the darkness, because he can't see the cross-wires in the reticule of his guide telescope. Only when the out-of-focus star disk is on or near these lines can they be seen on one of these inkwell nights. If by any chance the star should wander out into the unmarked region, it is next to impossible to bring it back without much lost time and trailing of the image. No matter how skilfully you estimate the center of the field, where the cross-wires should intersect, you always seem to guess wrong. This ruins your carefully watched images and causes perhaps a few angry ejaculations. At any rate, a light in the tube of the telescope, near the entrance port of the eyepiece draw tube, will solve all of these troubles. A 1½-volt flash light bulb, with a cheap rheostat to vary its brilliancy, will serve admirably for all conditions. Or, if the observer does not like the illuminated field and prefers illuminated cross-hairs instead, there is an equally simple expedient. The same bulb is placed in a little receptacle beside the reticule, as a part of the eyepiece. This throws a light on the wires themselves, leaving the field dark. Either method is equally efficient. One more suggestion is, that a green bulb is a great help. Green gives more contrast to the star against the field, and thus makes guiding on faint stars easier. Few stars or other celestial bodies are a Christmas-tree green, whereas other colors are more prevalent. A little experiment with these things will dispose of more personal idiosyncrasies. The best advice is: try it and see.

For those who like to play with spectra and such things, there is an unlimited field in wholesale spectroscopy with these little cameras. An objective prism large enough to cover the lens is all that is needed. There is a slight variation in the focus of the lens when the prism is employed, but in the case of small cameras and limited dispersions it is negligible. The difficulty is to get a 30° prism large enough for the lens. The easiest method is to make one. The carbon bisulphide prism can be made by cementing plates of good glass together, but this is a ticklish job at best, and the prism often leaks when you least expect it. The most direct method for amateurs is to hunt around for an old condensing lens of large

dimensions—one that some second hand dealer is ready to throw out—and cut a prism out of it. This isn't a big job, with a sheet metal disk and a quantity of No. 60 Carbo. This rough glass is all that is necessary in order to begin work on one of the most interesting of optical problems.

The figures of the flat surfaces need not be extremely accurate, but the more accurate they are the better—provided they do not look like the tool for a short focus Newt. It is well to have the line of intersection of the two planes perpendicular to the edges of these planes. Thus there will be a means of knowing where the axis of dispersion lies. A slight error makes little difference, but when it assumes the proportions of a single element for a Nicol prism, it is time to get busy. However it is not a difficult job; it just requires frequent testing with a known surface, and elbow grease. When it is ready to be used the procedure is to clamp it over the lens, with the base parallel to the celestial equator. This sends the spectrum along a north-south line. The thing to remember is that it is a line. The star, being a point, gives a line when stretched out. As the exposure is being made, some provision is needed for widening the spectrum. This is best accomplished by retarding the rate of the clock a given amount, so that during the exposure the image will trail to a width of about one half the length of the spectrum of each individual star. (For impulse drives it is easier to offset the polar axis 10° or so in azimuth). This seemingly excessive width is for more positive identification of the lines recorded. With a 30° prism, on a lens of 12″ focus, a dispersion of not more than ¼″ may be expected. This depends largely on the range of the plate in use. Ordinary supersensitive panchromatic plates are quite satisfactory for this work. Care must be taken to have the trailing of the image constant, otherwise there will be transverse lines running through the spectra, and these will prove to be annoying. Very interesting results can be obtained by this wholesale method of gathering spectra. A comparison spectrum is, of course, an impossibility, so the lines must be interpolated from known lines for their wavelength. However such things as the type and temperature of the star in question, as well as its condition of environment and many other interesting facts, can be determined.

There is still another phase of astro-photography that catches the imagination. This is the photography of doubles, the satellites of various planets and globular clusters. See Figure 6. This, of course, can be accomplished only by the use of a telescope of some sort. Fine lenses are absolutely necessary. They need not be expensive, however. Many pieces of excellent optical workmanship are to be found in the Army and Navy stores about the country. A quantity of fine periscopes, made by Ross of London, for the U. S. Army during the war, are sold at quite reasonable prices. In addition to a large 90° prism and an erecting train, they have an excellent objective and a good eyepiece for photographic work. The objective is undercorrected, while the eyepiece is overcorrected, giving approximately the required neutrality for photographic work. When these are mounted in a suitable tube, with a plate holder in focus behind the eyepiece, at the point of required

enlargement, they form a very serviceable telephoto camera. The distance of the plate from the eyepiece determines the enlargement of the image, also the speed at which the instrument works. The larger the image, the slower the speed of the optical train.

Assuming the objective to be 1½" in diameter, a speed of $f/25$ is about right. This gives an image of the moon about ⅜" in diameter which, although not large, is plenty for lunar detail when the photograph is subsequently enlarged (Figure 7, at left). The satellite system of Jupiter spreads to about

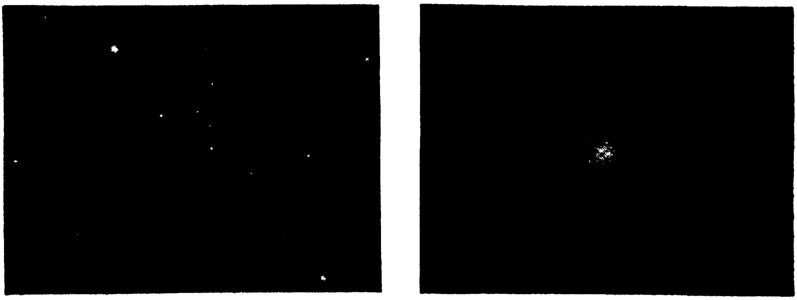


FIGURE 6

Left: Taken by the writer with an ordinary double convex reading lens working at f/3.5 and a press plate. Exposure 20 minutes. Milky Way in Ophiuchus. Right: Hercules Cluster M13. Telephoto lens of e.f.l., 37.5" working at f/25.

⅝", and in average weather requires an exposure of about 12 to 15 minutes. Double stars, such as Alberio and Mizar, are nicely split under a lens. Another boon to amateurs is the resolving of close globular clusters, such as M13. These open up very nicely but require very prolonged exposures, sometimes extending to eight hours or more. This, however, may be broken up into four-hour shifts on successive nights, or into even shorter ones. A good mounting and drive clock should make four hours relatively easy for an observer who has a little experience and a thorough familiarity with his instrument. In spite of this, there is a strong tendency to go to sleep and find the exposure recording the sunrise. A wrench, tied to the finger and held in the hand, is a good watchman. When the observer tends to nod, he drops the wrench and the jerk on his finger wakes him up. However, things are not always as sleepy as that. Comets and such are exciting things to photograph. The wrench may be dispensed with at such times.

A little discussion of plates may not be amiss. There are many plates on the market today, many of which are utterly unsuited to the amateur astronomer's needs. It is usually best to stick to the fastest plate on the market, so that exposures may be cut to the minimum. (Never take a salesman's word for it, either). The grain of these plates is large—true enough; but this is of little consequence when it comes to points for images.

The faster the better, and panchromatic if possible. "Pan" plates give more exact representations of the visual intensities than blue-sensitive press plates. But they have one disadvantage: they cannot be watched as well while coming up in the developer. Sky fog, or stray light in the sky, often restricts the length of exposure, because in time it registers on the plate, and if allowed to accumulate, it will often obliterate the image. This must be watched carefully during development, and the plate bathed in a stop bath or fresh hypo as soon as it appears. However, if it doesn't appear within the normal

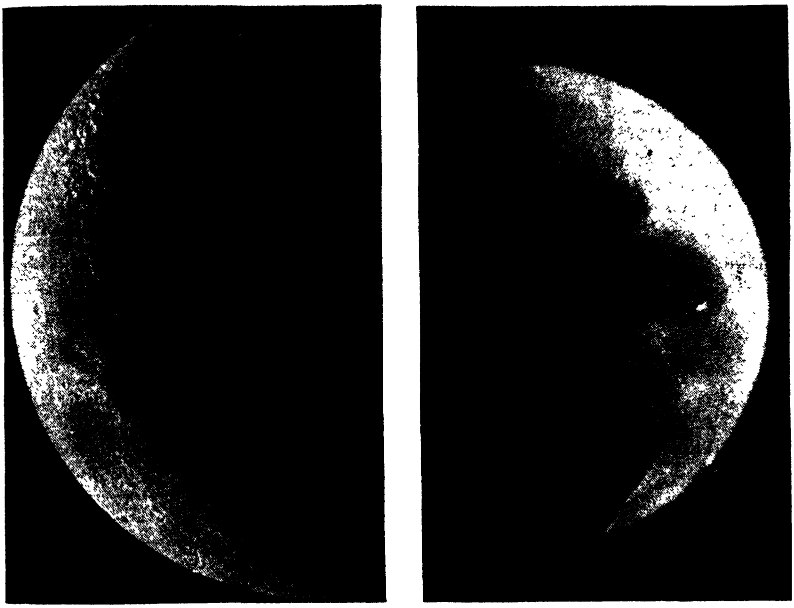


FIGURE 7

Left: The moon photographed with a telephoto camera such as the one described in this chapter. Right: A pinhole shot at the moon. Distance of the hole from the plate was 125".

developing time, it is safe to leave the plate in a little longer. This tends to fatten up the images, by developing the grains nearer the glass. Often nebulosity comes out which would be lost if the plate were developed only for the normal length of time. A word of caution here: beware of intensifiers; they do not agree with stars. Often an intensifier will bring out nebulosity that doesn't actually exist. It is always best to consider over-long development as the lesser of these two evils.

Infra-red plates are of little use in ordinary stellar photography, except for photographing through planetary atmospheres, which we are not considering here. They require long exposures and show nothing that blue-sensitive plates will not show, except, of course, more reasonable looking red stars. As for recording dark stars that give off low intensity heat radiations instead of light, don't waste your time. Their intensity, if they exist in the field at all, is so low that it would require weeks of exposure to record them. Try a number of reputable makes of plates and choose the one that, in your opinion, is best. Do not try to force your choice on the next fellow, for he too probably has his pet plate, and he might resent it. Whatever you choose, stick to it—in this way there will be a uniformity of conditions under which each photograph is made, which simplifies matters greatly when any sort of photometry or comparison is made.

Regarding developers, there is no criterion. Any developer that is contrasty and reasonably fine grained will be suitable. Even these restrictions are unnecessary. The formula of the developer has to vary with the properties of the plate, as well as the personal equation of the user. However, the more contrast, the easier it is to measure and print the plate.

A little experience with various plates and developers will never go amiss, and will give more information on the subject than a book. In time a definite routine for the processing of plates will be established, and things will go smoothly from then on.

This field of amateur endeavor is one that is comparatively virgin and is also one which permits great controversy. For those who enjoy optics, there is work to be done. For the more mechanically inclined, there is work to be done. And, still more, there are, connected with this work, photography, chemistry, electricity, physics, mathematics and philosophy, beside the major topic, astronomy—room and to spare for anyone to come along, take his pick of the list and go to it.

Solar Eclipse Photography for the Amateur

By John W. McFarlane and Walter Clark
Eastman Kodak Company

Items of Interest to Photograph During an Eclipse

Partial Phases: About one hour before the total phase, the moon may be seen gradually encroaching on the sun's disk, and for about one hour after totality the shadow gradually retreats. An interesting record can be made of the partial phases. A series of exposures may be made at intervals to show the progressive stages before and after totality. Some interesting records have been made by making exposures at five minute intervals on the same plate for a half hour preceding and a half hour after totality. The period over which such a record can be made on a single plate depends, of course, upon the angle subtended by the plate at the lens. The position of the sun will change about 15° per hour.

In the earlier stages, when only a small portion of the sun is covered by the moon, it is still quite bright and, while the exposure giving the best results would vary greatly according to the circumstances, an exposure of $\frac{1}{1000}$ second at $f/64$ on Verichrome film without a filter, or $\frac{1}{50}$ second at $f/32$ when a grey filter is placed over the lens, should be within the latitude of the film.

The exposures of the eclipse should be developed somewhat longer than the normal, in order to gain added contrast. If developing by the dark room tray method, using an Eastman film and photo-developer powder, develop for about 8 minutes at 65° F.

Shadow Bands: During the last two or three minutes before the sun disappears, and for the first two or three minutes after totality, wavelike shadows called shadow bands may usually be seen moving over the ground. They may be from one to two inches wide and five or six inches apart. They are most easily visible upon a white background.

Attempts to photograph this phenomenon will probably result in failure, on account of the low illumination and speed of the movement. Should the attempt be made, a short exposure (about $\frac{1}{100}$ second), a high aperture lens (at least $f/1.9$), and a high speed material will be required.

Supersensitive panchromatic film, with an $f/1.9$ lens, photographing a white sheet at $\frac{1}{100}$ second exposure, may give a record of the shadow bands.

Landscape During Totality: The intensity of illumination varies rapidly during the minute just prior to and succeeding totality. At the darkest period an exposure of about $\frac{1}{2}$ second at $f/11$ on Verichrome or Panatomic film should give good results.

Corona: In the inner corona Baily's beads and the solar prominences are of importance. The variation in brightness for different features of the

corona is so great that different exposures are required to obtain the best record of each feature. Suggestions as to the exposure may be found in the exposure table near the end of this chapter.

Flash Spectrum: To record the flash spectrum requires, in addition to the camera, a properly mounted prism and considerable experience on the part of the operator. The interested reader is referred to treatises on astronomy and physics for the technic of this sort of photography.

Lenses and Other Equipment

The size of the sun's image will depend upon the focal length of the lens. An easy way to calculate the approximate image diameter is to divide the focal length of the lens by one hundred. Thus, with a lens of 5½" focal length, an image 0.055" (slightly less than 1/16") diameter will be obtained. Such a picture will, of course show very little detail, though it can be subsequently enlarged. Panatomic and a fine grain developer are advised. In the case of motion pictures, the image will be enlarged by projection on the screen.

The *f* value of the lens used is the factor which determines the length of the exposure time.

Small Telescopes and Binoculars with Camera: A small telescope or binocular may be used in conjunction with an ordinary camera. In this case it is best to build some type of rigid support for both telescope and camera, and to arrive at the best focus experimentally by photographing the sun prior to the eclipse. An approximate setting can be made by focussing both the telescope or binocular and camera lens on an object at great distance before joining them.

A series of exposure tests with any optical arrangement to be used can likewise be made at any time prior to the eclipse, by photographing the sun. The data thus obtained should give reliable information as to the exposure for the partial phases.

Materials

For the most interesting phases of an eclipse, those occurring during totality, a high speed photographic material is desirable. Amongst the film materials Kodak Panatomic, Kodak Supersensitive and Kodak Verichrome, either roll or film pack, cut films or Eastman Safety Panatomic and Eastman Supersensitive Panchromatic and motion picture films, such as Cine-Kodak supersensitive panchromatic film, and supersensitive panchromatic motion picture negative, are recommended. Amongst the plates, hyper-Press, hypersensitive panchromatic, and speedway plates are the best. To avoid halation all plates to be used for eclipse photography should be coated on the back with Eastman opaque, if they cannot be purchased backed.

Exposures

(Calculated for Verichrome film or Cine-Kodak Supersensitive)

Lens Opening	*Filter*	*Time (seconds)*
	Partial Phases	
$f/256$	none	2/1000
$f/8$	neutral gray* density 3.5	1/25
$f/4.5$	neutral gray density 4.0	1/25
	Totality (Prominences)	
$f/8.0$	none	1/25
$f/4.5$	none	1/100
	Totality (Inner Corona)	
$f/8.0$	none	1/2
$f/4.5$	none	1/10
	Totality (Outer Corona)	
$f/8.0$	none	3.0
$f/4.5$	none	1.0
	Flash Spectrum with 40° *Prism*	
$f/8.0$	none	1.0

*Neutral gray density is a colorless gelatin filter. A density of 4.0 transmits 1/10,000 of the light, and would also be useful for visual observation, to replace the usual smoked glasses.

The use of neutral gray gelatin is a convenient way of cutting down exposure, prior to totality. It can be quickly removed from in front of the lens at totality. Suppose, for instance, that it is desired to make a Cine-Kodak motion picture record of the partial phases and of totality. This can be done with a 3″ $f/4.5$ lens, with a 4.0 neutral density in front of the lens, to photograph the partial phases at normal taking speed. If the filter is removed at totality and no other exposure change is made, a good record of the whole phenomenon should result. The inner corona will be slightly under-exposed and the outer prominences will be slightly over-exposed.

The same procedure can be followed if the 35 mm. motion picture camera is used. In this case a lens 6″ in focal length or longer is desirable. The aperture need not be greater than $f/6$ with supersensitive panchromatic negative.

For f values other than those given in the table the exposure can be calculated. The required time of exposure will be proportional to the square of the ratio of the f value used, to that given in the table. Example: Suppose the lens to be used has an f value of 64. To compare this with the f value of 4.5, given in the table, divide 64 by 4.5: equals 14+. Square 14+: equals 200. The $f/64$ lens will therefore require 200 times the exposure that the $f/4.5$ lens will require.

The Dewing of Optical Surfaces *

By Dr. W. H. Steavenson, F.R.A.S.

The deposition of dew on lenses and mirrors is often a source of great irritation to observers who work in the open air in damp climates. A few notes on methods of checking this nuisance may be of interest to those who have suffered therefrom.

Object Glasses: The dew-caps generally supplied by the makers are not sufficiently long to give adequate protection for several hours at a stretch. The obvious alternative of a longer dew-cap will often do all that is necessary, but even this will not always cure the trouble on the really damp nights. Moreover, there is an objection to long dew-caps which is not mentioned in the textbooks, and that is that, on calm nights, they encourage the formation of what may be called "dew-cap currents," causing the same sort of disturbance of the image as is brought about by tube currents in a reflector. On several occasions, while observing with a 6″ telescope in South Africa, I was troubled by these currents, and found a great improvement in the steadiness of the images when the dew-cap was removed. In England, however, this simple remedy can, for obvious reasons, seldom be adopted with impunity.

When my old 6″ Wray was mounted at West Norwood the object glass was at first very apt to become dewed, though the dew-cap was some 15″ long. But, after some experimenting, I managed to get over the difficulty completely by (1) keeping the outer surface of the glass very clean and free from those small particles of dust round which moisture so readily condenses; (2) lining the dew-cap with black blotting-paper, kept in position by the outward pressure of a helix of iron wire; and (3) jacketing the outside of the dew-cap and of the upper end of the tube with felt. This last expedient is perhaps the most useful of all, since it militates directly against the fundamental cause of all dewing—the excessive lowering of the temperature of the glass in relation to that of the air. Besides, if carried out still more thoroughly, right down to the eye end, it will help to check tube-currents, which are by no means negligible in the case of refractors with long tubes, used in the open air.

If, from neglect of these or other precautions, the glass does actually become dewed, it is better not to risk wiping it in the dark. The telescope should be brought to a horizontal position, and a roll of warm dry flannel or similar material should be laid inside the dew-cap, not quite touching the glass, and a close-fitting cover be placed over the end. After a few minutes the dew will be found to have disappeared. This method was recommended to me many years ago by the late Dr. Maw, and I have found it most effective. When closing down for the night the roll may be left in the dew-cap, closed in as above, in order to check any tendency to sweating when the temperature rises in the morning.

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* Reprinted by permission, from the *Journal of the British Astronomical Association* (January 1932).

Photographic lenses: These may be treated on the same general lines as object glasses, but the special conditions of their use render necessary or possible certain modifications of method. To begin with, long dew-caps are ruled out where it is desired to cover any considerable field. In fact with lenses of very wide angle there must be practically no extension at all beyond the lens mount. Under these circumstances dew may be kept off by one of two methods: (1) by drying the air in contact with the glass, or (2) by warming the latter artificially. Of these two methods, the first was successfully adopted by the late John Franklin Adams, who devised and made an apparatus for pumping dried air into the dew-cap immediately in front of his 10″ lens. A detailed description of the apparatus was given by him in *M.N.R.A.S.*, 1910 May and 1911 December. The second method is that which is used at the Harvard College Observatory. Here, on the Metcalf photographic telescope, four electric bulbs are fitted in light-tight metal covers, to the outside of the dew-cap. The heat thus generated is communicated to the lens through its cell, and no dew can form upon it. I have myself made use of the principle underlying this method, with very satisfactory results. The small wide-angle lens which I used for photographing the Milky Way at Pretoria had no dew-cap, and became damp after a few minutes' exposure to the sky. The trouble was very simply cured by tying a flash-lamp bulb, covered with lead foil, to one side of the lens mount. At the end of the two-hour exposures the outside of the camera was generally covered with a thick film of moisture, but the lens was invariably dry.

For obvious reasons this heating method is scarcely applicable to visual telescopes, especially where critical performance under high powers is required. But the pumping of cold dry air in front of the objective might, I think, be carried out without detriment to the performance of any telescope.

It has sometimes been suggested that the surface of a lens might be kept dry by the application of some such preparation as is used to prevent raindrops clinging to spectacle lenses and the windscreens of motor cars. But Mr. F. J. Hargreaves informs me that he has actually tried the experiment, and that it was not a success.

Flats of Reflectors: If placed some considerable distance from the open end, the flat will generally keep dry, especially if the tube be made of wood; but with a metal tube, or where there is much stout metal work in the flat mount or its support, dew will sometimes form. It can be driven off by the application of gentle heat, the warmth of the hand placed on the back of the mounting being sometimes sufficient in the case of the smaller sizes; or its cover, containing some warm dried flannel, can be put on it for a few minutes. But this is cure and not prevention. To prevent the actual occurrence of dewing it is a good plan to jacket the entire tube of the telescope, if this is made of metal. This will also do something towards checking the formation of tube currents. Where, however, the flat is very near to the end of the tube, and especially if its mount and supports are heavily built, such a precaution is not likely to succeed, and in such a case I can confidently recommend a method which I have lately adopted in the case of the 20″

reflector made for me by Mr. Hindle. It consists in applying a constant but very gentle heat to the back of the flat by means of a small electric bulb. I use a 4-volt flash-lamp bulb, fed by a 3-volt current, transformed from the main supply of 220 volts. The bulb is fixed inside the base of the mounting. It is covered with lead foil to make it light-tight, and between it and the back of the flat are several layers of cotton wool and tissue paper. The result is a very slight and very even heating of the glass, which is about 7/8″ thick and of 5″ minor axis. I had thought of this method more than a year ago, but had hesitated to apply it, as I thought it almost certain that the figure of the flat would be affected. However, I am glad to say that there is no perceptible effect whatever on the images of stars as observed with the highest powers, while the flat remains dry on the dampest nights, as it never used to do. It is interesting when closing down after several hours' work, to find the flat and its mount quite dry, while its heavy metal supports are running with moisture. The nearest point on the surface of the flat is only 4½″ from the mouth of the tube.

The Main Mirror: This seldom dews except when the temperature suddenly rises during the night. This immunity is chiefly due (apart from its situation at the bottom of the tube) to the fact that, being of relatively large mass, the mirror lags behind the surrounding air in its rate of cooling. This is especially the case with large mirrors, particularly when no part of them is in actual contact with the metal of the cell. But a small mirror, in contact with a metal cell, may occasionally become dewed. The best remedy is a jacketing of the cell and lower end of tube. An artificial circulation of dried air in the tube would also be effective, and would also, if sufficiently brisk, help to disperse slow-moving tube currents.

But what is really required is an effective and safe method of keeping a mirror free from dew when mounted, in the open air, in an entirely open tube. The idea of applying heat in any form to a parabolic mirror seems so obviously unsound from an optical point of view that one hesitates to suggest it. On the other hand we have to remember that a mirror, at any rate a large one, *is* losing heat to the surrounding air during most of the night. It is true that, as Mr. Ellison has pointed out, this cooling is accompanied by a change of figure, but only an abnormally rapid rate of cooling will produce so marked a change as to impair the performance of the mirror to a really serious degree. Moreover, as Mr. Ellison has shown, some sort of allowance for the average rate of cooling may be made when figuring the mirror. It occurs to me as possible that, by making a still greater allowance, good performance might still be secured from a mirror that was receiving a constant but *very small* supply of artificial heat. Possibly the scheme would not be a success, and there are certainly plenty of theoretical objections to it. On the other hand, after the surprising success of the heated flat experiment, I should hesitate to condemn it untried. I hope some ingenious person will make an actual trial of the method and report results.

Limitations of Vision with a Telescope

By H. E. Dall

Any optical instrument to which the eye is applied, whether telescope or microscope, is only a part of the complete optical system en route to the retina. The other part, and quite an important one, is the observer's eye. From the retina the pattern of the image is telegraphed via the sensory nerves to the sight center of the brain.

The optical system of the observer's eye is never perfect, and rarely so perfect that its defects do not noticeably affect the ultimate performance of the applied telescope. The lens of the eye is soft and pulled into shape by a large number of muscle fibers which unfortunately do not always pull evenly all round. The transparent cornea, too, is frequently not equally curved in all axes.

With naked eye vision, do you observe bright stars as points of light without perceptible area or appendages? The classical illustration of stars with spikes so well interprets the average naked eye view that quite a fair sprinkling of ordinary folk actually believe that the spikes are real appendages, without bothering to reason out why they see much the same assortment of spikes round a distant street lamp.

I would advise any of the A.T.M. community to try a little experiment which will teach them a lot about the defects of their eyes, and may even lead them to find they want spectacles! Some may have already tried it in the course of Foucault testing on mirrors. Look toward an illuminated, very tiny pinhole in the dark, from a distance of a few inches but without trying to focus it, (*i.e.* with the eye at rest, normally focussed for distance). A feeble pinhole is better than a bright one, as the iris will then be wide open. Use one eye at a time. Knowing as much about optics as all A.T.M. folks should, it is not hard to realize that the out-of-focus disk which they see *should* be perfectly round, or at least as round as the iris is—and I haven't yet seen any cats' eyes among humans. It should also be uniformly illuminated on the same assumptions of perfection. In actual fact it is rarely round—some bumps or irregularities or ovalness are usually visible even to a person with excellent sight. Similarly it is rarely of uniform brightness, for not only does the disk show a large number of radiating streaks, showing the imperfect homogeneity of the transparent striated muscular and other tissue, but there may be considerable variations of illumination between the center and edge of the out-of-focus disk.

In making the test there is an optimum distance for best examination between eye and light point. If too close, the sensitivity is reduced because the disk is expanded too much and small irregularities are not readily seen. On the other hand, if removed too far, the eye may struggle to focus it, and give a spiky star instead of a disk. A disk with an apparent diameter of 2 or 3 degrees, or say ½ inch diameter at 10 inches, is very suitable.

As an example, my eyes show disks like Figure 1, *a* and *b*, for left and right eye at a distance of about 6 inches. A myope (short-sighted) will

need to go closer to the pinhole, and a hypermetrope can increase the distance considerably.

Instead of an illuminated pinhole, a myope can use a distant street lamp, or an object like Venus. A normal or long sighted person can also use a distant light source by looking through spectacles of about +8″ focus (5 diopters). The out-of-focus disk in this case will reverse the axis on any astigmatic irregularity, as compared with the close test. As the rays are nearly parallel on the object side, this method lends itself better to knife-edge testing, or to measuring the iris opening or zonal irregularity, but the close pinhole method is quite convenient for general examination.

If the out-of-focus disk, expanded to the size suggested, has a nice, even, circular outline without bumps, congratulate yourself. More probably it will have some ellipticity with stray bumps. My eyes both give pear-shaped

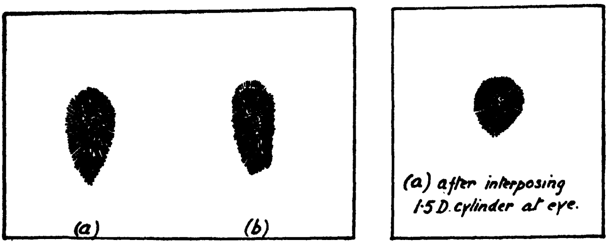


FIGURE 1

Typical out-of-focus disks illustrating defects in the eyes (negative view).

disks with local excrescences. If I interpose a cylindrical spectacle lens on the correct axis close to the eye, I can squash the pear to a much more circular shape. In my case about 1.5 diopters cylindrical is necessary to get to the most circular squash and this is the extent of my astigmatism—a moderate amount which necessitates wearing spectacles constantly. Borrow or buy a few cylindrical lenses, say .5, 1, and 2 diopters, and try for yourself. Astigmatism may be of the most irregular kind, and spectacles can then only make a rough approximation. Even if I attempted to figure a special lens to "iron out" the bumps, it would be of little use unless it was "glued" on the cornea. Incidentally, corneal contact glasses have been used to some extent, especially in Germany, and it would seem that these provide the best remedy for bad cases of irregular astigmatism or bumps, which are often due to the outer surface of the cornea. Fluid fills the space between the contact lens and the cornea, and the defective surface of the latter becomes practically non-existent optically.

Try cutting across the light cone close in front of the eye with a knife-edge. The shadow will advance from the opposite side on the close pinhole test and may distort itself on the passage across, showing up zones of unequal focus. Color fringes indicate the lack of chromatic correction of the eye, but the dispersion of the optical system is quite small. Make a scale

on a piece of glass, consisting of 11 small ink dots a millimeter apart, also make a separate dot 1 millimeter in diameter. Now, by using a distant light source by the second method mentioned above, interpose the glass one or two inches in front of the eye and allow the separate dot to traverse the beam. As it crosses, obviously the shadow seen should, with perfect sight, remain constant in diameter. In my case it is only about two-thirds as big at the center as at the edge, while if I traverse near the area causing the bump the dot almost explodes. A reduction of dot size at the center indicates a longer focus at that part, and vice versa. It is not difficult to plot a little map of the wanderings of the eye from focal uniformity and the aid of a little calculation will indicate the amount of the errors. The dot scale held similarly across the iris exit pupil will show the diameter of this very clearly. Mine varies from 7.0. to 7.6 millimeters in the dark. Watch it suddenly contract if a match is struck a foot or so away in front. A little belladonna or atropine will probably expand it to something like 10 millimeters.

The errors are much reduced, or the bad zones stopped out, if the iris contracts to its normal daylight size of 3 or 4 millimeters or if the pupillary aperture is restricted by a diaphragm or by a small eyebeam from an optical instrument. This is one reason why vision is often so much better on bright days than in dull weather, although theory based on the resolving power of the aperture would indicate just the reverse.

Resolving Power of the Eye: The retina has "grain" rather like a photographic film. The grain consists of the tips of a closely packed bundle of rod-like nerves constituting the retina. The packing is denser in the sensitive area known as the fovea, where the average spacing is .003 millimeters, and little evidence exists of any appreciable variations among individuals. Two close points of light can be seen as double only if they fall on separated nerve tips, and it will be apparent that this imposes a definite limit on the resolution of image structure by the eye.

By a remarkable example of Nature's economy this granular limit is coincident with the optical limit imposed by the resolving power of the average aperture of the pupil in bright daylight, *i.e.* about 3 millimeters. The indications are that Nature does not arrange to provide more nerves than is necessary to get the best out of the optical system of the eye, working at the aperture when the utmost performance is required. The same economy may also be shown in some of the lower animals, having regard to their habits.

The optical resolution of the eye is greater than that of a lens in air, owing to the homogeneous immersion system given by the aqueous humor.

From the above it will be clear that nothing can be gained in image quality, when using a telescope, by employing an eyebeam larger than about 3 millimeters and, *providing there is plenty of light,* there is no point in exceeding this aperture, unless it be required to give a larger field of view at the expense of aperture. On the other hand, if the illumination is feeble, the collecting power of the expanded iris can be used to the utmost with an

eyebeam 7 or 8 millimeters diameter. It is quite within the bounds of possibility that the spiral structure of certain nebulae might be just revealed to ocular vision (as distinct from photographic) if the observer, using one of the great telescopes, put a spot of atropine into his eye and used an eyepiece giving a 10–12-millimeter eyebeam! The method is not recommended if resolution of the detail is desired, as the chances of such an aperture giving an accurate retinal focus are remote.

The reference to eyebeam is to that point in the optical train near the eyepiece where the bundle of rays from the objective or mirror reaches its minimum diameter, after refraction through the eyepiece. It is also called the Ramsden disk, and its diameter (ignoring eyepiece aberrations and assuming that no stops obstruct the aperture) is equal to the O.G. or mirror aperture divided by the magnification given by the eyepiece. The iris feeds itself into the best position for the reception of the eyebeam by a process of "feeling"—almost automatically by a trained eye. A comfortable location for the eyebeam is ½″ or more outward from the eye lens. High power eyepieces cannot be designed to give this distance, so that in order to get a reasonable size of field the eye must be placed very close to the eyepiece. To view the full field it is not essential that the iris should be positioned exactly at the eyebeam, so long as the iris can accept the whole cone, but it must be borne in mind that the farther is the iris from the eyepoint the more can the errors of the eye affect the performance away from the axis. Eyepiece aberrations can also quite seriously affect the size of the eyebeam.

The Ramsden ocular is somewhat worse in this respect than the Huygenian, although the converse is true for the ordinary image aberration. This point is shown up clearly when fitting sky flooding stops to Gregorian or Cassegrain type telescopes. This stop must be placed exactly at the eyebeam and have an aperture equal to that of the eyebeam. Eyepiece aberrations can readily allow sky flooding to occur in such cases because the image of the mirror (which is the eyebeam) has a different position and size for each zone of the eyepiece traversed. A corrected doublet as a field lens will obviate the difficulty and avoid unduly large secondary mirrors, or having to waste aperture.

To sum up, if the requirement is maximum visual sharpness of image detail where the illumination is ample (*e.g.*, for lunar, or bright daylight views), and the eye is fairly free from errors, an eyebeam of 3 mm diameter is suitable. A somewhat higher power (12 to 14 per inch of aperture) is necessary to enable a keen eye to see *all* that there is to be seen in the image, though even then not without some strain. To examine the detail with greater comfort twice or even three times this power is more suitable—again if the light is ample, *e.g.* for lunar observation. For close double star work where the intrinsic image brilliancy is high, a yet higher power (50 or 60 per inch) enables the detail to be seen in greater comfort, even though it is vitiated to some extent by the wooliness caused by diffraction.

An observer with considerable astigmatic errors—particularly if very irregular astigmation is present, will often find great advantage in the use

of small eyebeams, and it is most likely that the observers who range themselves into opposite camps—the high power and the low—do so in virtue of the presence or absence of irregularities of the eye, also possibly to some extent to varying retinal sensitivity to light. The folly of dogmatic assertions as to which is the better is obvious.

In cases where the maximum light or contrast with feebly illuminated objects is required, *e.g.* for nebulae or for terrestrial observation at dusk or night, an eyebeam of 7 or 8 millimeters can be utilized. Obviously in such cases resolving power is quite of secondary importance.

For rich star fields, clusters, comet seeking or nebulae observation, the largest eyebeam that the dilated pupil can accept is desirable and, as mentioned earlier, to secure maximum results I quite seriously suggest that a non-injurious pupil dilator such as atropine or castor oil could be applied to the eye before any important series of observations. An eyepiece could then be used having an eyebeam 10 or 12 mm in diameter and giving the utmost attainable visual results for the telescope in use.

For general daylight work an eyebeam between 3 and 4 millimeters will fit the average pupil and will give an image, assuming of course that the optical quality is good.

Astigmatic Eyes: When observing with an eyebeam of 3 millimeters upward it is quite as necessary to wear spectacles to correct astigmatism as it is to wear them for reading or for normal purposes. The necessity is lessened to some extent for smaller eyebeams, and it would be a poor eye for which the necessity persisted much below a 1 millimeter eyebeam. Spectacles are decidedly a nuisance when observing, and to avoid them some observers have incorporated their astigmatic correction by cementing an appropriate piece of cylinder to the eye lens of each ocular. Another method is to utilize the astigmatism present in most eyepieces in the outer parts of the field to balance that of the eye. The observation is then confined to that part of the field where the errors are neutralized. Still another method I have employed is to use a "cantable" Barlow lens with a convenient means of adjustment.

Effect of Central Stops: Blocking out the center zone of a telescope (as with a secondary mirror or prism) definitely vitiates the image. The resolution of double stars does not suffer perceptibly, but some fraction of the luminosity of the spurious disk is extracted and thrown into the diffraction rings, with the result that contrasts of fine detail, *e.g.* planetary features, are reduced. The reduction of contrast and the loss of limb sharpness are quite appreciable for a central stop one-fifth of the diameter of the mirror.

It is quite an interesting experiment to block out the central 90 per cent of the mirror diameter with a card stop and note the exaggerated eliminating effect on fine detail. Note also the beautiful system of bright rings round a star disk!

Incidentally, planetary detail provides a much more crucial test of the performance of any telescope than does a double star. Zonal errors have

a greater effect on the contrast of such detail than on the size of the spurious disk.

Bearing in mind this effect of central stops, it will be seen that compromise is desirable between the conflicting interests of fully illuminated fields, short foci, and the bad effect of the stop. A method I adopted quite successfully some years ago in the case of a 14", $f/5$ Newtonian was to place a ¾" prism only an inch or so inside focus, and carry a specially figured triple cemented erecting lens on the support arm between prism and eyepiece. The final image was in a comfortable position, had a reduced angular aperture, and fully illuminated a field nearly half a degree in diameter, while the shadow of the obstruction was scarcely visible.

The Herschelian type conveniently eliminates the central stop, and if made with a focus not less than 16 diameters and a prism clear of the aperture to get a more comfortable observing position and prevent body air currents, the result should be well worth while. Should the observer suffer from astigmatism there is a good chance here to get some neutralization. An off-center cylinder can be interposed before the focus, to neutralize the errors of a shorter focus instrument due to the tilt of the mirror.

Some reflectors are made with central stops one third or more of the primary in diameter. Not only does this affect definition adversely and reduce illumination, but it is most annoying to use on low powers, on account of the obstructive effect of the blind spot in the eyebeam. If, for instance, a large field be required, giving an eyebeam say 7.5 millimeters in diameter, the blind spot will be 2.5 millimeters diameter, and if the iris is contracted to about 3 millimeters, the dodging required to get a view is anything but pleasant, quite apart from effects on definition.

The 200" telescope is to use a 33 percent secondary, and perhaps it is as well that photographic duties are paramount. For visual purposes a power of well over 1000 would be required to avoid bad disturbance from the secondary shadow without wasting aperture.

Diameter of Eye Lens: In order to illuminate fully the edges of the field of view it is of little use having a suitable margin on the prism or secondary, if the eye lens is insufficient in diameter and obstructs the convergence to the eyebeam. The diameter required to avoid any cut-off can be found by doubling the tangent of the semi-angle of the apparent field of view, multiplying by the distance from the eye lens to the eyebeam, and adding the diameter of the eyebeam.

For a 45° field, a power of 12 per inch and an eyepoint of ½", the eye lens diameter should be ½" minimum.

No stops should of course be placed to interfere with the cone of light forming the eyebeam, or cut-off will occur at the edges of the field.—*Luton, Bedfordshire, England, June 1935.*

Atmosphere, Telescope and Observer

By A. E. Douglass

[Editor's Note: The paper which follows is reprinted, by permission, from *Popular Astronomy,* June 1897. It is an old paper but it is a very good one, its content being as much to the point today as it was in 1897. When it was written its author was First Assistant at the Lowell Observatory in Mexico. Percival Lowell had temporarily moved the 24″ refractor to Tucabaya, a suburb of Mexico City, at 7500 feet elevation (Lowell—"Biography of Percival Lowell," page 68) and this is where the author made many of the observations described below. Later the author was Professor of Physics and Astronomy at the University of Arizona, where he is now Director of the Steward Observatory (36″ reflector, 4″ and 5″ refractors). His recent studies of climatic and solar cycles in tree ring growth—dating and providing data on climatic conditions of the past—are widely known, as are his earlier studies of Mars' and of Jupiter's satellites.]

It is a matter of importance and significance that so little has been done in recent years upon planetary detail by telescopes of great size. The strenuous effort to produce instruments of enormous power and perfection has resulted in telescopes of remarkable light-giving capacity, which have a true motion and are all that could be desired in convenience, but which do not show improved definition. There is no difficulty at all in assigning poor atmosphere as the cause of this because, with the exception of the Lick Observatory, the Harvard Observatory in Peru and the two stations of the Lowell Observatory, no effort of any moment has been made to place large instruments in locations directly selected for their astronomical qualities.

The 36″ of the Lick Observatory was in a sense the pioneer in this hunt for good surroundings but on account of the great size of the glass and the lack of comparison observations in even better latitudes it was impossible to estimate with any precision the relative importance of atmosphere and instrument.

The Harvard expedition to Peru was more successful. There, Professor W. H. Pickering, having at Cambridge, U. S. A., observed Mars through one opposition, was able to declare at once the superiority of the atmosphere. For the same reason he could indicate the difference between Cambridge and Flagstaff; the fact that for certain measurements of the satellites of Jupiter he habitually uesd a power of 1305 is sufficient evidence of the steadiness of the air at the latter place. Professor Pickering was unquestionably the first to intelligently appreciate the great importance of seeking a good atmosphere.

The result of our own experience in studying planetary detail has been to regard the atmosphere as of the first importance, the energy and the intelligence of the observer as of the second and to put last of all, the instrument, provided it gives a fair amount of light; but we find that the value of the instrument increases in an atmosphere that is reasonably near

perfect. These conclusions are derived from the continuous use of large telescopes in Peru, Massachusetts, Arizona and Mexico.

The atmosphere, then, is a factor of prime importance in the definition exhibited by large telescopes and its study becomes of corresponding consequence. Every astronomer knows that good seeing is not a matter of clouds, that the definition does not become superb merely because the atmosphere has become clear and perfectly transparent; on the contrary a certain amount of haze sometimes improves the seeing. Most astronomers have become aware of this fact and more correctly judge the seeing by means of the "steadiness" of the air. This is estimated chiefly from the twinkling of stars. Hardly one or two have gone beyond this and investigated the cause of twinkling and found the means for making direct observations upon the quality of the atmosphere for fine work.

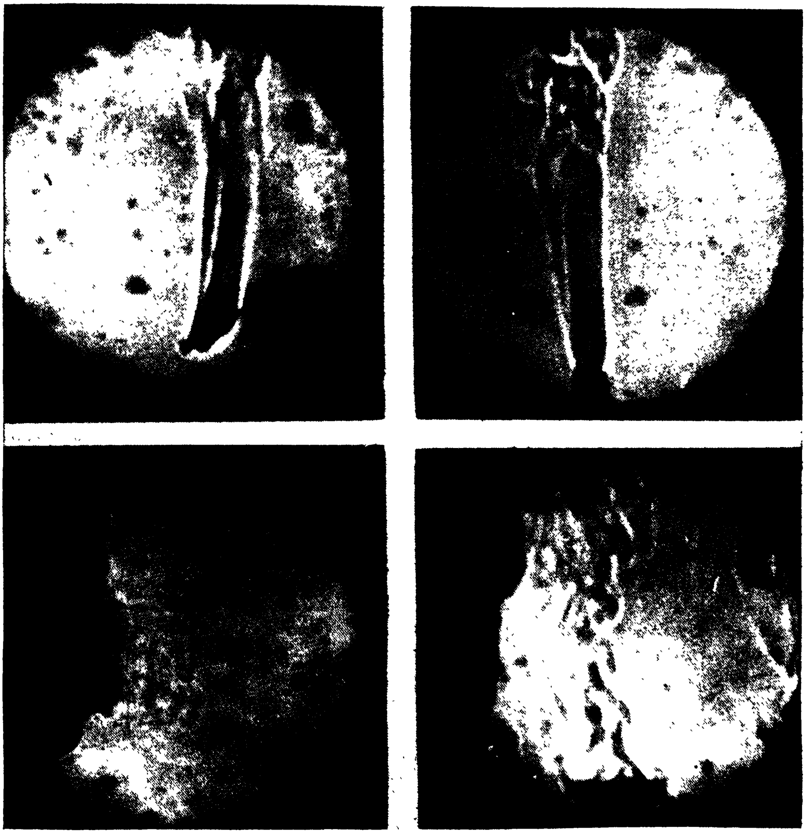
There are three media through which the light from a distant heavenly body must pass before being interpreted by the students of astronomy. And upon each of these three, Atmosphere, Telescope and Observer, it is our purpose to make some remarks, describing certain details of each that have come under our observation. Through the discovery of certain methods of studying directly the conditions of the air for astronomical work and the vast importance of obtaining favorable conditions, the larger and more important portion of this paper is devoted to the description of the origin and character of those methods. Taken in its entirety this treatment of the three topics is introductory to the study of the selection of observatory sites.

The Atmosphere; its Currents: Every possessor of a fair sized telescope has at hand a means whereby he may study the more obscure atmospheric conditions which accompany good and bad seeing and, at least in some cases, determine whether bad seeing is due to local conditions which may be evaded by moving a few miles, or to general conditions which may require a large change in latitude to correct. The means consist simply in placing the eye directly in the focus of the objective and watching the streams of air pass by overhead.

These currents were first noticed in this way by the writer, at the Harvard College Observatory station at Arequipa, Peru, in 1892. That Observatory is situated on the bank of a canyon-like river valley which drains some large plains lying 15 miles to the north and at some 5000 feet greater altitude. In the early night, if the sky is clear, the air becomes cold in the bottom of this valley and begins to flow gently downward. Soon it attains considerable velocity, spreading out over the more open valley below. Some hours after midnight its volume is such that it overflows its confines and submerges the Observatory, producing a sudden lowering of temperature and an immediate destruction of the seeing.

The movement could be felt as a fresh, steady, chilly breeze coming from the mountains to the north. By means of the objective it could be seen as a set of fine parallel north and south lines moving swiftly from north to south. This effect of lines moving longitudinally is of course the effect always

produced by an uneven surface passing rapidly across a small field of view, as, for example, the appearance of the ground between the rails when one stands on a swiftly moving train and looks down between the cars. The



Four photographs made by the author, from an arc light, at Flagstaff in 1900. They show the heat currents over a match, a candle, in the breath, and over a lamp chimney. Behind the heat source in each instance was a mirror.

absence of any such appearance in the objective previous to the arrival of this midnight wind amply proved the connection between these moving lines and the descending breeze.

This connection between the streams of air and lines across the objective was subsequently verified by an experiment tried on the great Yerkes lens

when it was undergoing tests at Alvan Clark's manufactory. A lighted lamp held before the objective produced a very conspicuous series of them, rising across the field. Any owner of a telescope can make a similar test by pointing on a star at low altitude and, while receiving the image of the star directly on the eye, having a lighted lamp or lantern held beyond the objective.

Beginning in September, 1894, the writer made observations upon atmospheric currents in the 18″ Brashear lens at Flagstaff. It was found that the direction of the currents and roughly their heights and velocities could be obtained. This discovery seemed chiefly to concern meteorologists and the results of the observations up to the end of the following December were discussed with especial reference to that subject in an appropriate magazine (*American Meteorological Journal,* March, 1895). From January 1 to April 3, 1895, observations were made at Flagstaff on every clear night and the astronomical importance of such work became more apparent. Since that time observations have been made whenever practicable and tests on artificially produced currents have verified the conclusions already reached.

One of the most striking instances of the use of these observations, was the discovery of the reason why some of the east winds at Flagstaff gave good seeing and others bad. When the seeing was good the currents seen through the telescope came also from the east but when the seeing was bad they did not do so at all. Instead, they came from the north or northeast and the mountain range extending from ten miles due north to about six miles east-northeast was shown to be responsible both for the change of direction in the surface movement and the very bad quality of the stream which was passing by at considerable altitude overhead. It seems probable from this that neighboring mountain ranges are not good.

The examination of the atmosphere by means of a lens is nearly the same operation as the test of a lens for ascertaining its correctness of form. In the ordinary test on a bright star the expert looks for the unchanging irregularities in the illumination of the objective; such irregularities belong to the objective because they are unchanging. In examining the atmosphere the observer notes the variable irregularities of illumination which must belong to the atmosphere because they do vary. He will see several kinds of variation in the illumination. The first, and one which is most familiar to us, is twinkling. This is most conspicuous with a very small lens—with the naked eye, for example—but on trial it has been seen nearly always in field glasses, very frequently in a 3″ lens, often in a 6″ and once or twice in an 18″ glass. It was once suspected in the 24″.

Different Kinds of Currents: In a large telescope there is one form which is called the "ordinary" current [No. 12. See note at end of paragraph.—*Ed.*], which is almost invariably seen. It consists, as described, in light and dark lines passing the lens longitudinally, varying in density, in rapidity of motion and in distance apart. Frequently—in some localities nearly always—there are two ordinary currents moving across the field, quite similar in appearance or, more rarely, quite unlike. Often also, when one current is

conspicuous a branch will begin to form, first having a direction nearly parallel to the main current and then gradually turning until it attains an angle of as much as 45° [Nos. 13 and 14.—*Ed.*], when it suddenly ceases.

[EDITOR'S NOTE: The series of illustrations of atmospheric current phenomena which begins on this page did not appear when the original paper was published in *Popular Astronomy* 1897, as the halftone process was not then in general use. But in 1936, when Prof. Douglass' permission was sought to reprint his article, he not only gave it, but in addition he sent some pertinent illustrations—sketches and notes on similar phenomena made by him February 21, 1899, which he kindly had photographed from his notebook of that period for insertion with this reprinted article in the present book.

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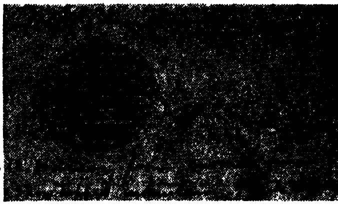

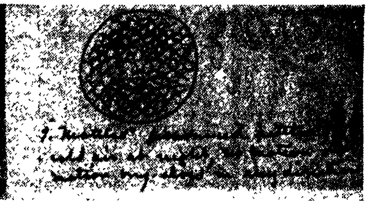
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While it has proved impracticable to arrange these in the original numbered sequence, the numbered references to those of them which correspond immediately with the text have been inserted between brackets. "These sketches," Prof. Douglass comments, "are somewhat unique, in that they give the identification of certain forms of currents in the air as seen by the eye. This was, of course, the main problem to the astronomer: he had to find out the locality of the interferences with his good conditions of seeing. This particular method made it possible."]

The form which is called "mottled" [No. 9.—*Ed.*] impresses one as something different but I am inclined to think that it is the ordinary current with a less rapid motion, for the reason that I have seen an ordinary current decrease in speed and become mottled. The fact which most strongly suggests its being a different kind, or at least having some special cause, is that it often causes the seeing to grow much worse. It is, however, always slow of movement and has the appearance of light and dark globules scattered over the lens. A similar appearance may be produced by pointing the telescope on a star at low altitude with or against the direction of motion of the most conspicuous current, thus reducing its apparent motion—a fact which verifies the idea that it is a slow form of the ordinary current.

There is another form, not at all common, which has certain similarity to the mottled but which arises from a different cause. It may be called "vibration" or "vibrating effect" [Nos. 13 and 14.—*Ed.*] and consists of light and dark globules upon the field that appear to pulsate without any marked change in position. I think, however, from carefully watching them, that this form is the result of two nearly equal currents of the ordinary form crossing rapidly at about right angles. When this is visible in a large in-

strument the lens of a small telescope appears to twinkle; and this is certainly one cause of twinkling to the naked eye—the crossing of the currents. The mottled form when moving very slowly could, I believe, produce the twinkling but the ordinary form moves too rapidly to allow the naked eye to perceive the variations of light it receives. Twinkling, then, usually means that there are two currents passing overhead in different directions, whose waves are farther apart than the diameter of the lens in use.

One form remains to be described; it is the "floating" [No. 7.—*Ed.*] or "syrup" form. It resembles in appearance the curved streaks produced by stirring syrup and water together and is very variable in its motion, seeming to float in the air above the objective. It is the most persistent of any

13 6

14 7

of the forms, having been absent only once or twice out of some hundreds of observations. In order to see this current distinctly it is sometimes necessary to decidedly change the focus of the eye, which fact suggests a very strong refractive power in the current. The waves are almost universally close together, long and irregular in form and have a tendency to suddenly start off with a rush in any chance direction.

The mottled and floating forms are the only ones which show their actual outlines in the air. It is probable that the shape of the waves in the ordinary form of current is similar to that of the mottled form; it is certain that it is not merely a longitudinal wave, because the variation it produces in the position of a planet is almost always equal in all directions. Both mottled and floating wave-shadows cast by electric lights on the sides of houses are often quite evident.

Methods of Seeing the Waves: The first and most direct mode of observing the atmospheric currents is by placing the eye in the focus of the objective. The currents cast, as it were, their shadows on the objective and, as all the light is concentrated in the focus, the eye can, without changing position, see all the irregularities in illumination which take place over that area, that is, in the cylinder which extends from the lens to the limits of our atmosphere in the direction of the star. In the case of a planet of sensible diameter this volume is a truncated cone with its smaller end at the objective,

instead of a cylinder. These differences of illumination are not real shadows but are condensations or rarefactions of light caused by the refractive power of the air. When, therefore, the objective brings all the light to a focus, the light from certain portions of the waves comes together inside the principal focus, and from other portions outside, so that an eyepiece may be placed behind these foci at proper distances and the waves seen through it. This operation will be referred to below.

The currents, of course, are usually observed at night but they may be seen in the daytime by using a small diaphragm at the focus to exclude the

15 15, Coarse currents, in great thickness seen on stars at low altitudes, large flickering coloured areas, with violet above & red at foot of each light area. Very [illegible] low altitude [illegible] has 11 & 15 combined, both highly coloured—e.g. on Canopus.

11. "Wrinkled", effect of looking through a great depth of settled cold air as in a valley or stars at low altitude,—is shown in any case when looking through great thickness of air from the [illegible], [illegible] or images from electric light [illegible] 11

greater part of the light of the sky. By day they are extremely handsome, and are characterized by an excess of the syrup form.

A difference is produced by the object at which one looks. The ideal object is a star in which the contrast in the waves reaches a maximum; in fact at times the little irregularities become so conspicuous that it is difficult to distinguish the more important main currents. A planet with a diameter of less than 30″ shows nearly everything in a fashion convenient for observation, but a large planet like Jupiter has often failed to show certain fine currents at all, or with difficulty, and has made coarse ones [No. 15.—*Ed.*] appear fine. This depends on the height of the current and is due directly to Jupiter's great diameter, as will be explained below.

Features of Atmospheric Currents: Direction.—The apparent direction in the telescope has to be reduced to the horizontal direction, so as to name the point of the compass from which the stream is coming. It is usually sufficiently accurate to hold a pencil so that it may be seen by the eye not at the focus, placing the pencil in the general direction of the current and then considering where it would intersect the horizon if extended.

Size.—This is also observed with the eye in the focus, and may be found by dividing the diameter of the objective by the number of parallel streaks which appear to cross it. This is a rough method but it gives all the accuracy required and is easily done. Such estimates should be made on a star or small planet and if at low altitude a rough correction should be made to find the size of the waves if they had been in the zenith.

Rate.—The motion of a current passing such a small field is very difficult to estimate except in the roughest way; the words "swift" or "slow" are usually sufficient to indicate what is seen. Slow currents should always be mentioned.

Conspicuousness.—This is one of the most important notes to make, as the seeing is directly dependent upon it. I have as yet been unable to form any direct standard of conspicuousness and it therefore becomes purely a matter of experience. It should always be remembered that the diameter of the object viewed makes a difference in the relative conspicuousness of different currents.

Constancy.—This refers either to continuousness of existence or steadiness of direction; usually the two go together, a current inclined to shift its direction being rarely permanent. This, however, does not apply to the floating form which is always changing direction and yet is practically permanent.

Height.—This is a difficult feature to observe because a scale has to be put on the sliding tube and the eyepiece run out until the particular current comes in focus. Owing to the extremely small portion of the lens which receives the graduations of light from a particular wave the focus is usually very indefinite—one has simply to do the best he can. The distances actually obtained are those of the points of convergence of light both above and below the waves, produced by the refraction in their slopes. Upon moving the eyepiece outside the principal focus the first focus reached is that of the highest system of convergent points which has anything like good definition; the next focus corresponds to the next lower set, and so on. If the refraction is such that one set of points would occur below the level of the telescope its distance behind the lens may be found by moving the eyepiece inside the principal focus (just as distances above the lens are found by the extension of focus). It is probable that only one set above and one set below the waves are sufficiently definite to produce foci. If the altitude of each of these sets is obtained, the altitude of the wave system must be halfway between them. I have attempted to verify this conclusion by actually comparing the distance apart of these two "principal" convergent planes as obtained by the change in focus and as obtained by the separation of the waves and their refractive power deduced from the vibration of the image in the focus.

The tabulated results are as follows:

Date 1895.	Altitude Wave-System.	Waves to convergent planes. By Focus.	By Vibration.
	feet.	feet.	feet.
Jan. 9	10,000	6,600	2,900
Feb. 19	14,000	11,800	10,500
Mar. 17	9,000	4,800	5,600
And on artificial waves,			
Apr. 24	290	18	83

The observations of April 24 were made upon artificially produced waves at a distance of 300 feet, through a 6″ telescope pointed upon an artificial star at a distance of 450′. The correctness of the distance obtained by change of focus, exhibiting an error of only three percent, is quite satisfactory and that indicates, as I had previously decided, that the chief trouble in this method of obtaining wave-heights is not in the focus but in estimating the amount of vibration due to a particular wave-system. This explains, I have no doubt, the disagreement in the last two columns, in two out of four cases above; and yet this estimation is of importance because often we have to depend for the altitude of the wave-system solely on the altitude of one convergent plane and the estimated vibration and size of waves. In making such observations I believe it is best to observe the lower limit of the upper convergent plane and the upper limit of the lower plane, when possible, and the maximum vibration that can be attributed to the system. The observed distance from wave to wave has to be divided by two to give the separation of adjacent slopes.

A correction must be made for the apparent altitude of the star in use, since the quantity obtained is a function of the distance of the waves from the objective. If the waves give good contrast and definition, this method is capable of considerable accuracy and might be applied to obtaining the height of well-defined and brilliant clouds. I have tried it on a terrestrial object which had a measured distance of 8.6 miles, with an 18″ objective, and obtained the results of 8.5 miles. It is well to note also whether a current seen without the eyepiece, shows more distinctly by throwing the eye out of focus.

Seeing.—Of course a record is always kept of the seeing but in this connection more precision is desirable. It is not enough to judge merely from experience, especially since we have the good and definite scale of seeing devised by Professor W. H. Pickering, which has already been published once in connection with this subject and which I give below in a slightly modified form, derived from, and therefore adapted to, a 6″ telescope.

With sufficient power (100 to 150 to the inch) the star image consists of a large central disk and a series of rings.

Seeing 12. Disk well defined, rings motionless, image motionless in field. Perfect seeing.

Seeing 10. Disk well defined, rings motionless, image moving in field.

Seeing 8. Disk well defined, rings complete but moving.

Seeing 6. Disk well defined, rings broken into dots and lines but still traceable.

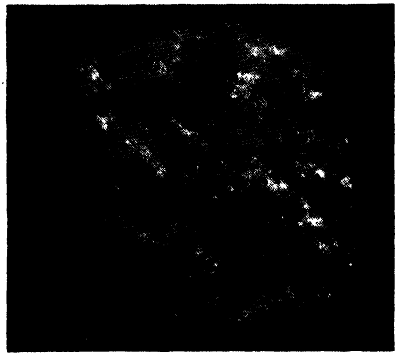
Seeing 4. Disk well defined, no evidence of rings.

Seeing 2. Disk and rings in one confused mass, constant motion, no increase in size.

Seeing 0. Disk and rings in one confused mass, violent motion, image greatly enlarged (for example, to twice the diameter of outer ring).

This scale of seeing changes with the size of the objective, but it may

be made complete by noting, in addition to the appearance of the stellar image, the character of its motion. In fact the ideal scale of seeing is one that depends solely on the motion of a stellar image such as would be obtained by a telescope of extremely long focus and very minute aperture. Perhaps some day when photographic plates are more sensitive, this observation will be made by photography; to-day it can be done by turning on a bright star, like Sirius, putting a very small diaphragm over the objective and setting the two micrometer threads at one or two seconds of arc apart and watching



Photographs of heat currents in the air in full sunlight, obtained by the author at Flagstaff in the summer of 1900. "A small telescope was placed on top of the dome at the Lowell Observatory," he writes, "and directed at my camera 4800′ away. A mirror was placed behind the eyepiece of the telescope, throwing a beam of sunlight through it. The eyepiece brought the sun's image to a small point, which then enlarged to the objective and gave a beam of nearly parallel light traversing the 4800 feet to my room in town. There a 13″ mirror brought the rays to a focus, and a few inches beyond focus the photographic plate was inserted. The exposure was made by a small slit in black paper, passed rapidly across the focal point." (For cognate data on the photography of shadow bands, by the author, see Astrophysical Journal, *April 1926, pages 188–190).*

the motions. Practically Professor Pickering's scale with a few notes on the motions of the planet or star is at present a less difficult form to give the observation.

Having directly compared a 24″ with a 6″ in the use of this scale, I find the 24″ wholly unequal to exhibiting many gradations of seeing which are of common occurrence. As nearly all observatories have a 6″ telescope, or one of about that size, or can diaphragm a larger instrument, I recommend the universal adoption of the above scale and aperture as the standard. By the present addition of seeing, 12, and the motion of the image in the field, the scale is made to cover those changes in seeing which are only of consequence in the use of enormous apertures under remarkably favorable atmospheric conditions.

Similar Phenomena: In order to understand the subject better, let me

cite a few familiar cases of the same or similar phenomena. The most ordinary instance is met with in sunlight upon shallow water. There, beneath each rising wave the light is condensed, while beneath each trough the light is enfeebled. At a certain depth, depending on the character of the waves, the contrast between the crest and the trough is most marked. Upon going deeper the difference decreases, leaving finally only light and dark patches. I conceive the waves in the air to be very similar in their action, though having a different origin and with an extremely slight refractive power.

Other very familiar examples are to be seen in the wavy motion of objects seen across a desert, across the top of a hot stove, or over a camp fire. I have often seen atmospheric waves upon the sunlit sill of an open window when the difference between the inside and outside temperatures was

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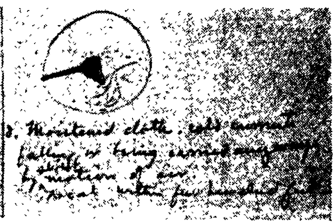

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very great. They show at night on the sides of white houses which are not too far from a brilliant electric light.

A less well-known case is that of shadow-bands or wave-shadows at the beginning and ending of a total eclipse of the sun. The reason that shadow bands are not always visible in sunlight is perfectly simple and exactly the same as for the fact already mentioned, that certain atmospheric currents do not become visible when viewing Jupiter. Each point on a light-giving disk casts its own set of shadow waves. When different points can be far enough apart for their respective shadows to overlap each other, an evenly illuminated surface results. That is what happens ordinarily with the sun and moon, and even with Jupiter. At the moment of a total eclipse, however, when the visible part of the sun is greatly reduced, they show, presenting undoubtedly an erroneous wave-form because the source of illumination is a line or thin crescent instead of a point or small circle. In the shadow bands of April 16, 1893, they were in the form of slightly curved wave-crests moving in a direction perpendicular to their length. This direction of motion would imply great similarity to waves on water, but we were left in some doubt as to the cause of this coincidence because their length was also roughly in the same plane with the visible crescent of the sun. They were observed at an altitude of nearly 4000′ above the sea. At sea-level they were at the same eclipse observed to be longer and perhaps less well-defined.

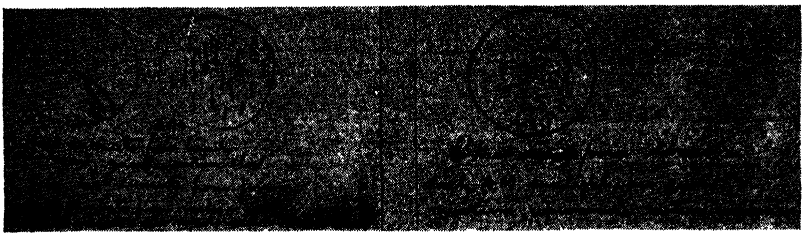
The absence of shadow bands of great size suggests that a large telescope can usually present to view all existing currents.

Causes of the Current Phenomena: The causes to which these phenomena are assigned have already been suggested but not as yet distinctly discussed by themselves.

These so-called waves are lines of irregular refraction in the air due to non-uniform density. The irregularities in density are due, I am convinced, to irregularities of temperature. The ease with which change of temperature may cause them, in comparison with change of pressure, may be observed in the following way. Wave a large, strong fan violently backward and forward in front of the lens when the telescope is pointed on a bright star; with great care the lines of pressure may be seen, resembling the curved wave that follows the tip of an oar in the water. Then try the bare hand in front of the objective, and the lines showing the movement of warm air from the surface of the skin are at once apparent.

The general cause of change in temperature, so far as I have traced them, are given below.

4 5 2



Convectional currents.—These seem to produce chiefly, and perhaps only, the syrup form.

Settling of cold air at night.—This settling occurs in valleys or level plains when there is not too much wind. I do not know its effect in an absolutely quiet air, but in valleys where it can have a downward motion it is productive of extremely bad seeing, with very conspicuous and rather small waves [No. 10.—*Ed.*].

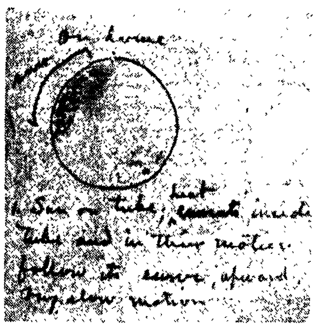
Mountains or Hills.—The experience at Flagstaff, already cited, indicates that when standing well up above the horizon they have a bad effect on winds passing over them.

Snow.—A Flagstaff experience similarly indicates that snow is extremely deteriorating. In each of these cases the size of the waves was merely a good average—neither large nor small.

Cloud condensations.—This theoretically, should cause changes in temperature, and clouds, especially moist clouds, actually cause changes in the appearance of the currents, making them coaser for the time being. It is difficult to say what is the cause of the coarse or fine currents, but it is possible that it depends on the humidity of the air.

Streams of air at different temperatures.—This does undoubtedly produce local changes of temperature, sufficient to cause bad seeing, but is obviously a difficult matter to study. In a very local way it may be investigated by a thermometer. I have been able to detect a rise of 2°F. at some distance to the leeward of a house; which shows how very bad a large city must be and the necessity of placing large instruments at considerable distance from them. In fact, the population of a region is a factor worth considering in locating an observatory.

Remarks upon the Floating Form: There is a very marked difference in this form between day and night. By day it is extremely conspicuous and



full of movement, at night it is often difficult to distinguish. It always moves about in the way that smoke does in a draughty room; it is very similar in appearance to the intense heat lines produced by a lighted lantern in front of the objective, or to the lines about the hand [No. 4.—*Ed.*] under similar conditions; it requires a great extension of the focus to bring it into view with the eyepiece. From these facts I conclude that it takes its origin in the layer of comparatively calm air that exists between the surface of the earth and the lower great stream overhead. It is in this layer that the main convectional movements occur by day. That, I think, is the reason for its greater conspicuousness and activity during that time. With a large planet like Jupiter it perhaps shows less change than the other forms, indicating thereby a low elevation.

It does not seem to exist in the telescope tube, because it shows no association with the outline of the lens; nor have I ever seen the entire lens vibrate, which would sometimes happen if there were currents of any consequence within the tube. Elaborate means have sometimes been taken to prevent movement of air within the tube but, after trying to see real evidences of such movement and failing, I am forced to conclude that none exist.

It is more difficult to say whether any of this current comes from the dome but, so far as I have observed, I am inclined to think not. For the comfort of astronomers in cold weather it would be well worth trying to

heat the dome, preventing the exit of any hot air near the tube by a rubber-cloth curtain which would hang down inside the shutter, entirely filling it, and be tied around the end of the telescope. By watching the currents of this character one could easily tell whether the heating did any damage at all to the seeing.

The floating form is the one most commonly seen without telescopic aid or in very small glasses such as surveyor's transits. Over dry ground, especially in tropical countries, its effect may usually be seen at midday with the naked eye. Owing to the source of light being an area instead of a point, no variation of illumination is produced, but the object becomes disturbed and distorted through the refractive power of the air waves. As one minute of arc is roughly the smallest angle visible to the naked eye under ordinary conditions of illumination we may easily put the refraction of these waves at 5 to 20 minutes of arc. Of course it must be constantly exceeding even these figures when the conditions are particularly favorable.

Effects of Currents on Seeing: The immediate dependence of the seeing upon the atmospheric currents is a continuous experience. With an increase in the number of the currents the seeing at once grows worse, and the direction of the current may have a large effect, some being habitually bad and others always good. The cause of such difference is to be sought for in local topography or in general climatic conditions. The conspicuousness of a current is its most directly influential feature, as it is a direct result of the refractive power of the waves, and upon this depends the vibration of the object in view and its consequent distinctness of outline and detail.

The refractive powers of the various telescopic forms of waves, are as follows: The ordinary form rarely exceeds 1 to 2 seconds of arc, while its usual amount is much less, say 0.3 second. The mottled form has an average of about 1 second and goes up to 8 seconds. The floating form has usually a low refractive power at night, but when very bad may reach up to 10 seconds. The ordinary form which is caused by the settling of cold air at night sometimes considerably exceeds this, even reaching 25 seconds, and that due to snow not infrequently comes near it. These figures are derived from observations on the motion of Mars in the focus and are given from a brief examination of a large number of observations. There is so much variation in the recorded amount of vibration that these figures can only be regarded as general approximations.

The average characteristics of waves of the ordinary form observed in Arizona and Mexico (each at an elevation of about 7000′ above sea level) were as follows: direction, westerly; size, 1½ seconds, and rate, roughly 10 miles per hour. The average size of the floating form was about ½ seconds.

The Telescope; its Apertures: Bearing in mind the foregoing facts in regard to the constant presence of air waves which are only a few inches apart and have a measurable refractive power, it is no difficult matter to deduce the conditions under which certain apertures become preferable.

It is easily a matter of observation that, making allowance for the variation in brilliancy of the apparent field when the eye is in the focus, the atmos-

pheric currents are precisely the same in telescopes of different apertures at the same time and place. This is of course what should be expected. But different apertures do change the character of the seeing; and this also is what we expect. Conceiving the waves to consist of crests and valleys, as the waves on water, we see that the refraction takes place on the slopes between these, and that two adjacent slopes refract in opposite directions. If we take the distance from crest to crest as d, and the mean amount of refraction in each slope as r seconds, we shall find that, in a telescope with an aperture of $\frac{1}{2}\ d$ or less, the image in the focus will oscillate through a distance of $2\ r$. If the aperture of the telescope is d, we would see in succession, if the waves were all of perfect form, first a haziness of the planet, then a displacement of r seconds in one direction, then a haziness, followed by a displacement of r seconds on the other side of its original position, then a haziness as at first, and so on; the haziness in each case being due to the presence of two slopes at once before the lens. If the aperture were $1\frac{1}{2}\ d$ there would be alternations of haziness with these displacements of r seconds, the displacements themselves being not entirely free from haziness. With further increase of the size of the objective, displacements would for a time exist, but become more and more hazy until at last they would cease, leaving the planet perfectly steady but blurred.

Such is the effect of using different apertures. As a matter of fact we rarely have such simple conditions in actual experience. We have a given telescope and usually three series of air waves which may be all of different sizes. By a big diaphragm we can get rid of the blurring effect of the largest set. By medium and small diaphragm we can improve successively the bad effect of the other series, but in doing so the light is enormously decreased. We may summarize this matter of aperture by saying that the smaller the aperture the more bodily motion and less confusion of detail; the larger the aperture, the less bodily motion and the more confusion of detail. This leads us directly to the aperture required for certain classes of work. For seeing planetary detail we should use a small aperture unless the seeing is at its very best. On the other hand, for micrometer work, when steadiness of the image is required, we need a large aperture. On one occasion, after taking a large number of diameters of Mars and assigning weight to each measure, I found that the agreement of the readings was almost inversely proportional to the assigned weights. I then remembered that I had judged the weights according to the distinctness of the limb and detail. Upon changing my criterion to the steadiness of the image in the field, the weights then become of real use in judging the relative value of different measures. Of course, there is a limit to which this increase of aperture may be carried, for the planet may become so ill-defined that micrometer measures are worthless. One has to tell from experience when this limit is reached.

Good seeing then, apart from transparency of the air, consists of two factors, steadiness and definition. In a given atmosphere these factors vary with the aperture, one being improved at the expense of the other; either one may come from a superior atmosphere. Let no one therefore be deceived

in attributing to his atmosphere what is really due to the relation between the diameter of his telescope and his class of work. For an accurate record of the quality of the seeing I earnestly recommend observers to use the scale already given.

Eye-end Diaphragms: It is usually rather inconvenient to put on and take off diaphragms, so it is worth remembering that to a large extent the same effect may be produced by using small diaphragms over the eyepiece which cut down the pencil of light entering the eye and so reduce the affective area of the objective. For a given diaphragm the amount of reduction varies with the focal length of the eyepiece. These eyepiece diaphragms have been tried by the writer to great advantage.

This idea of placing obstructions between the eyepiece and the eye has a further use. The field of light about a very bright star is largely due to chromatic aberration, the impossibility of bringing all colors to the same focus. Through the refractive effect of the atmospheric currents and sometimes through the projection of opaque objects into the circle of the lens (for example, tin-foil separating the glasses) this field, consisting of many concentric rings, is divided off into series of rays. In searching for faint companions to bright stars these rays are extremely objectionable and anything which will help to get rid of them will be of value.

The objectionable field light produced by any given point in the objective lies almost entirely across the focal image, in a line parallel to one joining that point and the center of the lens. Therefore, by placing across the objective or behind the eyepiece bars of suitable size, all the field light may be cut off in a line parallel to that bar without making any very great loss of light. Experiments may be made in this line by merely thrusting a knife-point in front of the eyepiece.

The Observer; Optical Qualities of the Eye: Aperture has another effect on the seeing, which is of different kind, namely, physiological. It principally concerns observers of planetary detail and doubtless has frequently been explained by them.

All the effects of this kind observed, vary with the size and brilliancy of the pencil of light entering the eye. The first imperfections noticed are motes which float about and persist in coming upon the planet which is under examination. They can also be seen against a clear blue sky. They often have the appearance of minute twisted hairs and sometimes show signs of cell-like structure—a fact which is more than suggestive, because they undoubtedly are the remnants of cells floating in the liquids which fill the parts of the eye-ball. When they come upon the planet they may be dislodged by a quick motion of the eye to one side, but that is only for the moment, as it seems to stir up a commotion and others quickly follow. With these, as with other imperfections to be mentioned, their maximum conspicuousness belongs to a certain intensity of light. With very bright sources of illumination they do not interfere; yet their range is very great and I know of no possible way of getting rid of them. To the naked eye they are perhaps a little less likely to appear under faint lights because the pupil is enlarged and they

must be very close to the retina to throw any distinct shadow. In telescopic work their probability of appearing is inversely proportional to the square of the diameter of the pencil of light which enters the eye, and they are therefore less likely to appear with low powers. High powers have the further disadvantage that they greatly reduce the apparent light of the planet and often render the motes more conspicuous in comparison. From their apparent size, when projected on Mars, I infer that their real size within the eye is between one and two one-thousandths of an inch.

Another region in which imperfections occur is the outer surface of the eye. These become visible when the pencil of light entering the eye is extremely minute and of the proper brilliancy, by the casting of their own shadows, as it were, on the retina and the absence of enough light from other parts of the pupil to drown them. With extremely high powers they begin to appear, and it need hardly be added that high powers show more of the imperfections of the eyepieces for a similar reason. These imperfections in the eye are extremely small and consist usually in streaks or drops of moisture, bits of dust and lines of compression, probably on the cornea.

Lack of correctness in the curves of the refracting surfaces of the eye is another source of trouble. Such general imperfections as myopia or astigmatism can be fairly well corrected by glasses, but there may easily exist in many eyes somewhat more local irregularities of curve which glasses cannot help and which therefore spoil the definition of the eye. It is a well known fact that some observers prefer high powers and some low. It seems possible that one cause of an instinctive preference for a high power may be certain local imperfections in the surfaces of the eye because, if fairly large, these imperfections interfere less with the small pencil of light emerging from high-power eyepieces than with the larger pencils from low-power eyepieces. For persons with eyes defective in this way there is a real advantage in using high powers.

But perhaps the most harmful imperfection in the eye is the lack of homogeneity within the more dense transmitting media, either the lens or membranes, probably the former. Under proper conditions the lens (presumably) displays irregular circles and radial lines, the whole resembling a spider-web structure. Under actual tests this structure is so very prominent that we wonder how the eye is able to give such good definition as it does. No optician could ever sell a lens so badly made, except for the coarsest usage; in proportion to its size it has the imperfections one finds in the lens of a bull's-eye lantern.

A most simple and instructive method of examining one's own eye is by taking two double concave lenses from a pair of opera glasses and looking through them at a candle some 10′ distant; by holding one lens near the eye, and moving the other backwards and forwards, the illumination may be adjusted to produce the best contrasts. In the experiment the pupil is seen as a circle of light and, if the candle is bright enough, concentric interference rings may be seen at its edges. After a few trials the motes in the eye, the irregularities in density in the lens or membranes, and the drops and streaks

of moisture left by the eye-lid, may all be seen. It is probable that irregularities of the refracting curves, such as spherical aberration and astigmatism, can also be made evident by this device. In spherical aberration the center should appear brighter or fainter than the edges, while in astigmatism there should be a bright or dark band across the center from side to side, in a direction depending directly on the line of astigmatism. It is possible, however, that spherical aberration could be produced merely by throwing the light into the eye in this unaccustomed manner, just as it may be produced in a telescope by reversing the lens. Minute local errors may be seen as light or dark spots and the semi-permanent effects of holding the lid closed by force for a moment, impresses one with the fact that such usage of the eye is very bad for its power of definition.

One might guess at the errors of curve quantatively but if sufficiently large they can be actually measured by using a telescope, micrometer and artificial star. Let the micrometer be illuminated from one side, and put a very small stop on the telescope so that the emergent pencil shall be very small. Under these conditions the entire pupil will receive the light from the threads but only a very small part of it will receive the light of the star. By passing the pencil of light through different parts of the pupil the error of any one point with regard to the whole may be obtained. It is possible that this usage of the telescope, combined with a slight spherical aberration in the eye, is sometimes a cause of the "parallax" attributed to eyepieces. By carrying this process to an extreme one might even measure the refraction in those minute permanent marks in the eye which become evident upon careful examination. These marks are about one one-hundredth of an inch apart, so that a pencil of light as small as one two-hundredth of an inch would be required for measuring them.

Contrast: This is a subject but little understood, although it is of great importance in research upon planetary markings. The elementary fact is that high powers greatly reduce contrasts; when one changes from a low to a high power the light parts of the planet become correspondingly fainter but the dark parts seem to become lighter; a perfectly black marking, however, such as the shadow upon Jupiter or one of its satellites, remains practically unchanged in good seeing. In an experiment for testing the effect of illumination on contrast, eyepieces were placed in the 24″ telescope and its 6″ finder, so that a magnification of about 200 diameters was produced in each. Jupiter was examined and, although work on the 6″ would have proved more difficult, owing to the greater conspicuousness of imperfections of the eye, no special difference in contrast for the larger markings could be perceived. The same result was obtained upon trying a power of 750 in each instrument. It was therefore concluded that illumination, and probably the size of the spurious disk and the size of the emergent pencil, have practically no effect on contrast within a large range, but that magnification has. Illumination however, does affect color contrast, for the greater the illumination, the more brilliant and conspicuous are the colors.

No doubt the chromatic aberration of a lens (its scattering of light in

a large field about the focus) has much to do with contrast; for the scattered light from each point on a planetary disk helps to reduce the contrast on all other parts of the disk within a certain distance. If we consider for a moment the image in the focus, it is apparent that this destruction of contrast will be the same in two lenses of the similar curves and equal ratio between the aperture and focus, no matter what the actual aperture be; but it is also evident that diaphragming a given lens will reduce scattering and tend to aid contrast, or, to express it differently, long focus lenses should be beneficial to contrast. We conclude, then, that, as well as improving the seeing, diaphragming may improve the contrast, provided the disk is not decreased too much in brilliancy, and that diaphragming a large telescope is better than using a smaller instrument of shorter focus.

Seeing, of course, has an effect on contrast because the refraction in the air waves causes a spreading about of the light from the object in view. Dust on the lenses causes loss of contrast, for a similar reason. But under given conditions of seeing the marked effect of a change in power cannot be due to seeing, because there is no relative change in the size of the object under examination, the atmospheric waves and the lens.

Apparent contrast, then, is a function of the size of the impression on the retina. The only explanation that suggests itself is this: The part of the retina most sensitive to slight contrast is the "yellow spot" which is also most sensitive to definition. It is quite likely that, after a faint marking becomes large enough to be seen at all, it will show maximum contrast when its retinal image holds a certain relation in size to the yellow spot. For markings of different densities it is possible that this dimensional relation changes.

The eye has considerable power of adapting itself to contrast occurring in different intensities of light, in a manner entirely independent of the size of the pupil. This has often been exemplified in the experience of visitors looking at Mars, when the emergent pencil was much smaller than the pupil of the eye; at first they see nothing but a glare of light but after looking sometimes for 15 minutes the glare diminishes and markings begin to appear. This is a certain power of adaptation which I have never seen mentioned before. After much practice that first glare becomes less and less noticeable and the eye becomes more sensitive to the particular range of contrast sought. That, in fact, is the training required by the eye to discern planetary detail, and for different planetary bodies which present different degrees of contrast and different intensities of light, the training has, to a certain extent, to be undergone afresh in each case.

It is a result of this training, helped, perhaps, by some natural difference in eyes, that two observers may find contrast more marked and detail easier in entirely different intensities of light. This point is best exemplified by the fact (very familiar to ourselves) that, of two observers examining Mars on alternate nights, one saw extensive and intricate detail in the light regions of the planet and the other observed numerous markings in the dark parts; but that, for the entire opposition, neither one saw much of importance in

the other's region. The sequel is interesting, for during the opposition just passing each one has made a special and continued effort to train his eye for markings in the other intensity of light, and so far succeeded that each has corroborated the other's previous work. This corroboration was not due to prejudice but to perseverance.

He will greatly benefit work in planetary detail who constructs an apparatus for increasing contrast. The polariscope has been tried with success upon clouds in our own atmosphere, because it darkens the background of the sky. In astronomical work we need some medium which, without spoiling the definition, will cut off all the light which comes from the delicate gray-green or blue tones of planetary markings.

Observer: The observer has already been mentioned as ranking very high in order of importance. It is not merely that the best observers of planetary detail are able to recognize what they see, and draw it, but it will be noticed that they have been very diligent in working often on unpromising material and amidst discouragement from other laborers in the same field. To everyone, at first view, all fine planetary work seems almost impossible and that is why all those who do not pass through this first stage discredit results that are finally proved to be of the greatest value. If one would see something he must persistently and persistently keep at it, picking up bits of detail, little by little, even though the seeing seems bad and the object difficult; always and only with the stern determination to see something if that something exists. The final pleasure of seeing his disjointed observation take shape in once consistent whole, is his reward.—*Lowell Observatory, Mexico, April 2nd, 1897.*

[Editor's Note: When planning to reprint here the rather old article just read, we were accused of being an archeologist! It was dug up, it is true, and from early deposits at that—1897. The article was found in 1928, when systematically turning the pages of the library files of *Popular Astronomy* from the Old Stone Age on, in search of possible buried treasure to reprint because not very accessible to the average amateur, but the present has been the first opportunity to reprint it. There was no inclination to let the mere conventional technicality of its age stand in the way, the article itself being valuable. The aim in similarly reprinting several articles as chapters in the present volume is to bring good matter together in a single place. Though most articles are available in large libraries, large libraries are not usually available or *handy* to the average reader.

After reading the original article from a photostat copy sent him, Harold A. Lower (who, with Alan R. Kirkham, seconded the motion for its inclusion here) wrote the following:

"We had already tried some of the stunts mentioned, as well as another, which I believe should be tried by others who are interested in the causes of bad seeing.

"Several years ago the local paper used to publish daily reports of the temperature and humidity at each 1000′ elevation, up to 17,000′. These

reports were obtained by an aerographic flight from the Naval aviation field at North Island. Unfortunately, there was no mention in these reports of the wind direction and velocity at different elevations. Even so, we found that the reports gave one a chance to see what effect was produced by changes in temperature and humidity at different elevations. For more than a year, we watched these reports, and checked seeing conditions.

"Briefly, we found that the principal cause of bad seeing seemed to be temperature reversals. Also, the magnitude of the disturbance depended on two factors, the amount of the temperature reversal, and the height at which it occurred. Small reversals at low altitudes did not injure the seeing very much, but a small reversal at high altitudes did. Fully 75 percent of the reversals occurred at altitudes below 6,000′ which would indicate that a mountain top observatory should be above a large percentage of the disturbance.

"Humidity seemed to have very little to do with seeing, except as it might influence the formation of clouds. Surface temperature and humidity at the point of observation were minor factors, although we did notice that the best seeing usually occurred on nights when the surface humidity was high. Some days there would be two or more reversals at different altitudes. This invariably was followed by extremely bad seeing that night."—H. A. L.]

Star Tests for Telescopes: The following tables are taken from Sir John Herschel's "Outlines of Astronomy," 1872—chapter on double stars.

2″ to 4″		4″ to 8″		8″ to 12″	
alpha	Piscium	alpha	Crucis	beta	Orionis
beta	Hydrae	alpha	Herculis	gamma	Arietis
gamma	Ceti	alpha	Geminorum	gamma	Delphini
		delta	Geminorum		
gamma	Leonis	zeta	Coronae Bor.	zeta	Antliae
gamma	Corona Aus.	theta	Phoenicis	eta	Cassiopeiae
gamma	Virginis	kappa	Cephei	theta	Eridani
delta	Serpentis	lambda	Orionis	iota	Orionis
epsilon	Bootis	mu	Cygni	f	Eridani
epsilon	Draconis	xi	Bootis	2	Canum Ven.
epsilon	Hydrae	xi	Cephei		
zeta	Aquarii	pi	Bootis	12″ to 16″	
seta	Orionis	rho	Capricorni	alpha	Centauri
iota	Leonis	upsilon	Argus	beta	Cephei
iota	Trianguli	omega	Aurigae	beta	Scorpii
kappa	Leporis	mu	Eridani	gamma	Volantis
mu	Orionis	70	Ophiuchi	eta	Lupi
mu	Canis	12	Eridani	zeta	Ursae Major
rho	Herculis	32	Eridani	kappa	Bootis
sigma	Cassiopeiae	95	Herculis	8	Monocerotis
44	Bootis			61	Cygni

Reflectors versus Refractors *

By William H. Pickering
Mandeville, Jamaica, B.W.I.

Having experimented with reflectors now for four years, and having been familiar with refractors for over 40, the writer has arrived at certain conclusions that may possibly interest some professional astronomers, and which he thinks should be of use to some amateurs. There are now but two kinds of astronomical investigation that are really worth while, open to possessors of small or medium-sized telescopes, whether they are professionals or amateurs. For those having small telescopes, those of 5″ aperture or less, there is only one—the observation of long-period variable stars. For those possessing telescopes of larger aperture, we will say from 8″ to 15″, the fascinating field of planetary research is also open, provided their climate is a satisfactory one. Telescopes of 5″ to 8″ aperture can also occasionally be used to advantage for such investigations. This class of work, however, requires good seeing, and it is therefore difficult to do much that is useful with any telescope in our northern states. This necessity of working in a comparatively low latitude, when good definition is required, has now I believe at last become generally recognized by astronomers. The *main* reason why a low latitude is desirable is in order that we may avoid the atmospheric circulation of the anticyclones. But even in hot summer weather the seeing in the north is seldom satisfactory, though not so bad as in winter. Secondly, in summer, even when the seeing is fair, then is the time when all the planets are nearest the southern horizon at opposition, that is, when they are nearest to us. This is because the ecliptic is farthest south at that time. The importance of this reason is particularly marked in the case of the planet Mars, on account of the striking changes that occur upon its surface at the favorable apparitions occurring in June and July, and to a less extent in August when it is still near us. Thirdly, although of less consequence than the other two, at all times the planets are seen at higher altitudes in southern stations. I have found that even some professional astronomers thought that this was the chief advantage of going south to observe. In reality it counts for very little as far as America is concerned. It is doubtful unfortunately if very much valuable planetary work can be done north of the Ohio River.

Oddly enough, on the other side of the Atlantic, they often have excellent seeing in the British Isles, when they can see anything at all through the clouds. This fact is well illustrated by their early discovery of a dozen of the Martian canals long before Schiaparelli ever looked at the planet, their well-known British modesty having prevented them from ever acknowledging the fact. They accordingly waited for an American to find it out. Thus Procter's map, based on Dawes' drawings of the apparition of 1864, shows the following canals: Hydraotes, Nectar, Agathodaemon, Sirenius, Brontes, Erebus, Styx, Cerberus, Eunostos, Nepenthes, Nilosyrtis, and Protonilus. The

* Reprinted by permission, from *Popular Astronomy*, March 1930.

last two, however, together with Nasamon, were discovered by Sir John Herschel in 1830, and some of the others by Lockyer, Lassell, and others. Secchi at Rome in 1858 discovered Ganges, which gives the Italians an early claim, although no priority. Beer and Maedler mapped Nectar and Agathodaemon in 1840. I do not say this of course to disparage the work of Schiaparelli, which needs no support from me, but merely to state a fact illustrating my statement that they sometimes have good seeing in the British Isles. The explanation of this is doubtless because of their moist climate, which we now know favors good seeing. Thus on 15 nights of comparatively poor seeing in Jamaica in the years 1914, '15, and '16, the mean dewfall averaged 3.6 cubic centimeters per square meter of horizontal surface of blackened iron. On 13 nights of practically perfect seeing the dewfall averaged 108.1 cubic centimeters, or just 30 times as much. (*H.A.*, 82, *B.F.* 37.) Indeed, whenever we have a calm clear night with heavy dewfall, the seeing is invariably practically perfect. On the continent of Europe the seeing appears to vary with the latitude, much as it does in the States. We gather all these results in part from our own experience of over 20 years in the torrid zone, and in part from the numerous drawings of Mars that have been sent to us from all over the world during the past 15 years.

An Inexpensive Mounting and Shelter: Turning now to the instrument, if one has to buy it, there is no question but that the amateur of moderate means will get more for his money with a reflector than with a refractor. If he can make it himself, he will obviously make a reflector. On the other hand if the observer is located in a southern latitude, has good eyes and enthusiasm, and can afford it, a refractor of the same aperture as a reflector, and costing three or four times as much, will show far more fine detail on the Moon and planets. It will of course require a 50 percent larger dome, or shelter, also adding to the expense. The amateur's reflector rarely exceeds 12″ or 13″ in aperture, and about 10′ in focal length. For planetary research it is not worth while to buy a refractor whose aperture is less than 7″ or 8″, since one can do nearly as well with a reflector costing less money. The only forms of reflector in use at the present day are the Cassegrain and the Newtonian. On account of the difficulty of grinding the hyperbolic mirror, the former is used only for large telescopes. Another objection to this form, at least for studying planetary detail, is that the comparatively large size of this mirror, usually about ⅓ or ¼ that of the parabolic one, causes extensive diffraction rings, or if the rings are not visible as such, an equivalent amount of scattered light, which is unavoidable. Even with a ratio of ¼ the equivalent focus is likely to be exceptionally long, unless the focus of the parabolic mirror is quite short. This again involves difficulties of grinding. Practically all small reflectors therefore are of the Newtonian type. The very great inconvenience of this form when the focal length approaches 10′ is that the observer's eye has to be at the top of the tube, instead of at the bottom, as in a refractor. Moreover, in order to observe an object south of the zenith, the best place in the whole sky for studying planetary detail, it is necessary to make use of a movable wooden bridge. Moving about in the

dark on a rather shaky platform four or five feet above the ground, if persisted in, may result in a rather disagreeable fall. The writer always illumines his bridge by an elevated electric light giving about twice the light of the full moon.

In order to avoid this defect of the Newtonian reflector the writer described a form involving only two mirrors, and involving no change of position, except when the object transits the meridian. The observer must then move within an hour or so from a comfortable seat on one side of the pier to a similar one on the other side. Moreover, he always looks nearly horizontally into the telescope, thus to a considerable extent avoiding moving specks within the eye. It is only when looking at an object in the far north, which is at the

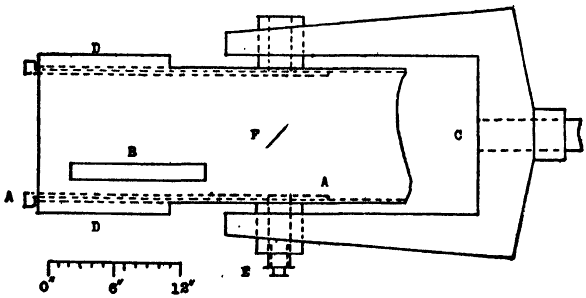


FIGURE 1

same time far from the meridian, that he needs to look up or down at a considerable angle. This is, in fact, the only form of reflector of any kind using but two mirrors and permitting a comfortable stationary seat. Moreover it makes use of a fork mounting, so that the telescope never has to be reversed. This is of especial advantage to planetary observers, and to those who wish to photograph objects near the meridian with long exposures. As in all mechanical devices where considerable advantages are secured, there must be some sacrifices. The chief one is that the tube must be about half as long again as in the ordinary form of Newtonian, in order that the single counterpoise may not be more than twice as heavy as the mirror. The second disadvantage is that there is a region surrounding the north pole with a radius of at least 20°, but not exceeding 30°, which cannot be observed at all. In the latter case we lose one-fifteenth of the northern heavens. It is a very uninteresting region, however, its southern boundary passing between the five well-known stars of Cassiopeia and the two pointers of the Dipper. This obviously does not trouble planetary observers, and this form of mounting has the somewhat compensating advantage that it can probably be constructed more cheaply than any other equatorial form hitherto proposed.

It is fully described in *Popular Astronomy*, 1926, 34, 570,* the accompanying schematical drawing being repeated in Figure 1.

A further great advantage of this form of reflector is that it is not necessary to revolve the mirror or the tube at all, but only a light inner tube carrying the flat. On account of the distance of the counterpoise as at present arranged, this is now done by means of a short slot in the outer tube shown at *A* in Figure 2. A pin which can be passed through this slot enters one of a series of holes in the inner tube, permitting it to be turned, so that the observer may look through either end of the declination axis as is desired. In

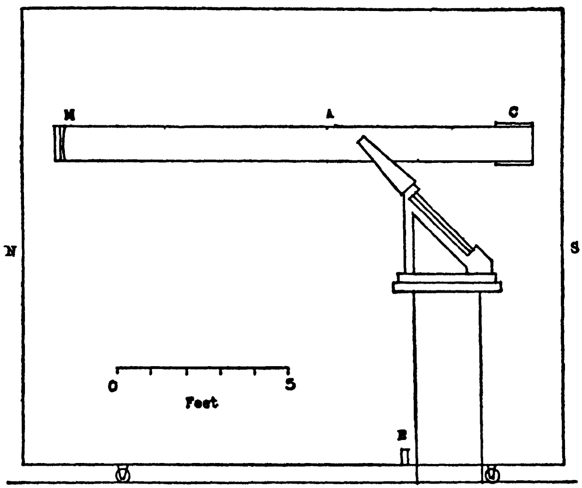


FIGURE 2

Figure 2 the telescope is shown as stored in a tent-shaped shelter in the form of an equilateral prism. This shelter may consist of a wooden framework covered with wire netting and canvas, or with sheet zinc. It rolls away to the north over an iron track, the wheels on one side being grooved to fit the rail, and on the other side rolling on a flat surface, thus avoiding all danger of binding. A door 2.5′ wide and 10.5′ high in the southern end of the prism permits this motion. There can of course be no threshold, and no

* EDITOR'S NOTE: The description referred to by the author runs as follows: "The length of the telescope could be anything desired—as long as a refractor if convenient. I have drawn the tube 12″ in diameter. The breadth of the casting of the fork at the end of the polar axle *C* is assumed to be 6″. It might be narrower. The distance from this point to the center of the flat *F* is 18″. The mirror is not shown, as it would be beyond the figure to the right. The light from it strikes the flat, and is reflected through the short declination axle to the eyepiece *E*. Either end of the axle can be used, and in order to do this the flat is supported by tube *A*,*A*, which rotates within the telescope tube. A hole in these two tubes transmits the light from *F*. There is no need in this case of rotating the large mirror. One of the finders is shown at *B*. There should be another similar one on the other side. The counterpoise ring is shown at *D*,*D*."

floor frame south of *B*. A removable brace could however be put in if desired, but none is found necessary here where a similar arrangement has been in use for the past 15 years. The observer sits on a high chair whose seat is 7′ to 7.5′ from the ground. A flat box 5″ thick which may be placed on the seat will permit of adjusting the body to observe objects when the eye is above the level of the intersection of the axes.

The Question of Air Currents in the Tube: The reason why a reflector for the same aperture is inferior to a refractor is at least three-fold. In the first place there are very effective air currents of varying temperature in the tube of a reflector—that is to say if the tube is solid or covered, and all small reflectors on the market at present have solid tubes, that is continuous metal or wooden tubes, as distinguished from those which consist of an open lattice work of metal. All the large modern reflectors, on the other hand, have lattice work tubes. They also are all mounted inside of domes, which is frequently not the case with small reflectors, which are often used in the open air with a hinged shelter, or one rolling away on a track. There appears to be a considerable divergence of opinion among the users of these latter as to the best form of tube. It is evidently a matter of very great importance, but does not appear to have been discussed in print heretofore. Dr. F. O'B. Ellison writes from Ceylon that while in Egypt he "tried both open and covered tubes, and found that the open was the better there," but later in Ceylon in a moister climate he writes, "I have taken your advice about covering the whole of my telescope tube and find a great improvement in definition resulting." L. J. Wilson has the two ends of his tube covered, in order to keep the dew from forming on his mirror and flat. The middle section is open, but he says he gets better results if it is covered with paper. He thinks that the paper protects the air in the tube from the warmth of his body. G. H. Hamilton's tube is similarly arranged, but he prefers an open middle section. Of course the temperature at night, which never falls below 60° in Jamaica, is higher than in Kentucky, and it is possible that this may in part explain their divergent opinions. However, Ellison preferred a covered tube in a warm climate, while in Egypt, where he preferred an open one, the nights are cold, at least in winter. Messrs. Phillips, Hargreaves, and Peck used an 18″ mirror, at first in a solid wooden tube. On substituting an open one for it they found a very striking improvement, Hargreaves even going so far as to write, "The performance of the 18″ in its skeleton tube has caused us to revise our views on the reflector versus the refractor question. In a skeleton tube we are convinced that a mirror gives at least as steady an image as an object glass." This appears to me to be a rather extreme view, if by steady is meant as clear an image, and while it might be true with what we should call moderate seeing in Jamaica, I am very sure it would not hold when the seeing is really good.

We all know when first starting a furnace in the autumn, that the hot air does not at once pour out of the flue, but is for a time blocked by the cold air already there, and which floats on top of the hotter, lighter medium, later gradually mixing with it, and finally being forced out into the room.

If we could look through those mixing masses of air in the tube, we should find the seeing intolerable. It occurred to me while using my reflector that that was just what was occurring within the iron tube of my telescope. When the shelter is rolled away, and the instrument is exposed to the outside air, the upper end of the tube is cooled by radiation to the sky, while the lower end, not so completely exposed, retains some of its original warmth. We accordingly have within the tube a mass of cold air resting upon a mass of warmer material. Since the quality of the seeing is not influenced by the velocity of the air currents, whether within the tube or in the sky, no matter how high that velocity may be, but is strongly influenced by the least difference of temperature, I determined to go to the bottom of the matter and collect the fundamental facts. I therefore procured three ordinary thermometers, and after comparing them side by side, I hung one with its bulb about 4″ below the flat, and another so that when the tube was vertical the bulb was just over the mirror. The third thermometer was placed under the wooden bridge close at hand. The middle section of my iron tube was always sheathed with wood. The lower section was never sheathed, and the window near the mirror was always left open, in order to give as good a circulation as possible. A thin blackened tube of pressed wood fiber was fitted just inside of the telescope tube, extending down as far as the flat. Its object was to cut off radiation from the inside of the tube.

In four series of observations the upper section was left unsheathed. In four other series it was sheathed with asbestos, and in seven more it was sheathed with wood. The first observation of each series was made immediately after opening the telescope for the night, usually between 6:00 and 9:00 o'clock, the last was made about two hours later. The 15 series were made on 14 nights, between January 22, 23, and March 4, 5, of 1927. The average temperature under the bridge at the beginning of the observations was $68^\circ.0$, and at the end $65^\circ.1$. The temperature at the bottom of the tube was nearly always higher than it was under the bridge, or at the top of the tube. The average difference of temperature between the two ends of the tube in the four cases where the upper end was unsheathed, at the beginning of the observations was $+1^\circ.1 \pm 0^\circ.3$, and at the end $+1^\circ.5 \pm 0^\circ.4$. In the four cases where it was sheathed with asbestos the difference at the beginning was $+1^\circ.7 \pm 0^\circ.3$, and at the end $+1^\circ.5 \pm 0^\circ.8$. In the seven cases where it was sheathed with wood the difference at the beginning was $+0^\circ.8 \pm 0^\circ.7$, and at the end $+1^\circ.1 \pm 0^\circ.7$. Three conclusions were arrived at, first that sheathing the upper end of the tube with asbestos was worse than leaving it unsheathed. This was apparently due to the asbestos collecting moisture from the atmosphere and actually becoming wet. Second, that sheathing the upper section with wood was an improvement, and third that, although the temperature at both ends of the tube fell as the evening wore on, that at the top of the tube fell faster, thus gradually increasing the difference in their temperatures.

The obvious remedy to employ is to use an electric fan, forcing a current of air from the window near the mirror up through the tube. Care must be

taken to support the fan in such a manner that it shall not jar the telescope. A 6″ fan is plenty large enough. With poor seeing, due mainly to currents in the upper air, the improvement resulting is not marked, but with good seeing it is most striking. It is very nicely illustrated by throwing a bright star out of focus before turning on the fan. The image usually rotates, sometimes in one direction, sometimes in the other. The rings always visible in such an image constantly vary in shape, with an appearance that we may describe as "moulding." The instant the fan is turned on all is instantly changed, the rings become circular, and all rotation ceases. Mr. Phillips in a recent paper speaks of having tried an "electric blower" but does not seem to have been quite satisfied with the result, because trouble began "as soon as the blower is stopped." (*Journ. Brit. Astron. Assoc.*, 1929, 39, 113.) In my original paper describing the use of a fan, Report on Mars No. 41, I state that an "electric fan sending a current of air through the window near the mirror, and up through the tube, was later found to give greatly improved results." (*Popular Astronomy,* 1928, 36, 451.) It did not at that time seem necessary to me to state that the fan should be kept going. In order to avoid jar I always support it on a cushion.

Since the opinions as to the relative advantages of open versus closed tubes are so divergent, it appears to me likely that with neither form are the mixing air masses entirely avoided, and that each observer should settle which is the best form for his own individual case. However, when an electric current is available, I feel that a closed tube with a fan entirely avoids the whole difficulty, and is therefore better than any open tube can be. Indeed in my recent Report on Mars No. 43 I recommended a similar arrangement to be tried on all large refractors. In such a case the best plan would perhaps be to employ a blower in place of a fan, and either suck or drive the air out of the tube. As a result of this investigation it now appears plausible to believe that the reason why a large refractor shows little if any finer planetary detail than one of moderate size is, not as I formerly suggested, that with a larger diameter it takes in more atmospheric waves, blurring the image, but that it is simply a question not of diameter, but of length. Reducing the diameter of the lens by a diaphragm up to a certain point undoubtedly improves the definition, but this is because the effect of the cold air currents moving down the sides of the tube is cut off by the diaphragm, leaving only the warm upward currents near the center of the tube. It appears probable that for either a reflector or a refractor better seeing would be obtained, in a good climate, if the diameter of the tube was appreciably larger than the diameter of the mirror or lens. In case a fan is not available, a wooden tube is better than one of metal. For a large refractor with a long tube, there is a greater range of temperature of the air within it, and a longer column of mixing air of different temperatures than with a smaller one. By blowing or sucking out this air, there will be a constant current of uniform temperature passing through the tube, giving greatly improved definition. As long as the air is of uniform temperature, the speed of the current makes no difference as far as the seeing is concerned. In the case of the Lick

telescope, one rather wonders what might be seen on Mars on a really good night, if the air within the tube were kept at a uniform temperature. It might give us rather startling information. It would seem almost a duty to try it.

The Diffraction Rings: A really good refractor of any size up to 12″ to 15″ aperture, with really good seeing, and a 1/4″ eyepiece, should show a bright star as a round perfectly uniform disk, surrounded by two or three fainter complete rings, which with the best seeing will be stationary or nearly so. I was once at a meeting many years ago, of the American Astronomical Society, where were present at least 20 or 30 professional astronomers, and someone asked the question if anyone present had ever seen a star disk surrounded by rings. To my very great astonishment only one or two others besides myself admitted that they had ever seen the appearance. With a 1/2″ eyepiece and good seeing I have seen as many as a dozen rings about a really bright star such as Arcturus, with a 12″ refractor, but it requires much better seeing to see two or three nearly stationary rings with a 1/4″. Anyone can see the rings with an ordinary spyglass by cutting down the aperture to about 1/12 of the focal length, and using a high power eyepiece. With so small an aperture the rings will of course be faint. I have never seen the rings with any reflector using the full aperture, but with my 12″ Calver stopped down to 5.5″, or about 1/20 the focal length, I have seen portions of them surrounding the central disk. This is probably the best that it will do, while with the Harvard 11″ refractor complete rings were by no means an unusual phenomenon. This shows at once that even as good an optician as Calver could not grind a mirror that would give definition at all comparable even to an early Clark refractor.

A much more important cause of the inferiority of the reflector depends on the brightness of the diffraction arcs. These vary in width and brilliancy with the seeing. They are never narrower than the spaces between the successive arcs, and may be 1.5 times as wide. When the seeing was good I have seen the arcs only half as wide as the diameter of the disk, but when it is bad, the arcs then shorten to rounded dots which are practically of the same size and brightness as the disk itself, and on account of their rapid motion are often indistinguishable from it. These observations were all made with my mirror stopped down to 8″ or to 5.5″, giving a ratio to the focus of 1/14 to 1/21. A bright star was always selected, usually Vega. With a 3″ refractor, whose ratio of aperture to focus was 1/13, the rings were 0.7 as wide as the spaces between them, and 0.25 the diameter of the disk. We may say in general that the rings with a refractor are but one-half as wide as those given with a reflector. The important difference between the two classes of telescopes, however, lies not in the width, but in the relative brightness of the arcs and disk. With the reflector I have seen the brightness of the arcs no greater than that of the disk, but when the seeing deteriorates it is often 3 or even 5 times as great. In such a case the effective diameter of the combined blur of light may be 5 times the diameter of the disk. With

the refractor, with good seeing, the combined light of all the arcs or rings ranges from about 0.05 to 0.10 that of the disk.

This astonishing difference between the two instruments it appears is not due to any fault of the mirror, but to the little considered, but most injurious, flat. If we place a round paper disk somewhat larger than the flat outside of it, the arcs at once increase in number and conspicuousness. On the other hand if we place a small eccentric diaphragm over the end of the telescope, so that the light transmitted by it does not strike the flat or its supports, but proceeds directly to the mirror, the seeing at once appears to improve, the arcs fade out, and the general appearance is that of a star as seen in a refractor. This plan has already been adopted by Professor Douglass with his 36″ mirror in his studies of Mars. By employing a 13″ eccentric diaphragm, his results are comparable to those of a 13″ refractor, and, as is seen by Report on Mars No. 43, as far as confirmed canals are concerned he ranks next to Trumpler. When a refractor is pointed on Mars, the image formed at the focus consists of a great number of minute disks of varying brilliancy, each one being of the size of a stellar disk. Over these is superposed a thin veil composed of the combined faint images of the diffraction rings. On the other hand in the case of a reflector, the image consists of a series of overlapping splotches of light of the effective diameter of a stellar disk and the surrounding arcs combined. It is no wonder then that with good seeing a reflector gives inferior results to a refractor. The only surprise is that it should give as good results as it does.

The reason why the 100″ on Mount Wilson shows such good planetary definition is probably that with so large an aperture, the combined disk and arcs are so small as to be comparable to the stellar disk alone of a much smaller refractor. It is quite possible that, even for planetary work, a refractor of the highest grade is not usually necessary. For instance, no 12″ refractor is conceivable which would give such large stellar images as a 12″ reflector, and of course such a refractor is always better, and would doubtless be better even if it were a pretty poor specimen of its kind. It is only in localities where the seeing is of the best, and perhaps for large refractors where the internal cold air currents are destroyed, that the advantages of a really first class objective should become manifest. In closing this portion of our paper, it may be said that we find that there are two important reasons why a reflector is inferior to a refractor of the same aperture. First, on account of the cold air currents in the tube of the reflector, and second, on account of the bright diffraction arcs due to the flat.

There is one important point that should be mentioned in this place. Many years ago, when I did more stellar astronomy than at present, I made a brief study of the diameters of star disks and rings. (*H.A.*, 61, 43.) I was then struck by the fact that when the focus was long in proportion to the aperture, in a ratio of perhaps 1/100, the image of the star resembled its theoretical shape, with a hazy disk much brighter at the center than at the edges, and comparatively faint rings. With an ordinary telescope and good

seeing, as is well known, the disk is uniformly bright, and the inner ring only slightly less bright intrinsically than the disk itself. A year ago I took the matter up again. The focus of my reflector as above stated is 113″, that of my finder 12″. I stopped both down to a 1″ aperture, the magnification of the reflector being 50, and that of the finder 40. I turned on Capella and two diffraction rings came out nicely in the finder, and I could just see the third. With the reflector one ring came out faintly, but the disk was still bright, though perceptibly less so than in the finder. I then reduced the aperture of the finder to 0.6″. The first ring with the two instruments was then equally bright, no other rings were visible, but the star disk was much fainter in the finder. This experiment clearly indicated that the rings were much brighter in proportion to the disk with the shorter focused instrument. Whether this matter has been discussed theoretically I am not aware, and have no means here of finding out, but every astronomer who has seen the disk and rings knows that in an ordinary refracting telescope, with a ratio of aperture to focus of 1/16, the edges of the disk are much brighter than the theory as applied to minute apertures demands, and these observations indicate that the same is true of the rings. The 16′ mirror of the California Institute of Technology is to have a ratio of its aperture to its focus of only 1/3. Such an aperture can hardly show rings, perhaps not even rings of dots under terrestrial conditions of seeing, but it is very certain that every bright star image will be surrounded by an exceedingly brilliant blur, due to diffraction, and far exceeding the size and brightness of the stellar disk itself. It is highly probable that a somewhat smaller mirror of longer focus, and therefore easier to construct, and much cheaper, but requiring a more expensive dome or shelter, would give finer definition, but for direct photographs of remote nebulae, and spectroscopic work, where definition such as we require on the planets, is of little consequence, doubtless the present proportions will give satisfactory results. It appears very doubtful if it will give any better definition than the present 100″, but it will perhaps release that instrument for more planetary work should it prove on further tests to give better results than less expensive refractors. On the two nights on which I tried the 100″ on known delicate lunar detail it impressed me favorably, particularly as I was told that the seeing was then only of average quality.

Wooden Tubes for Reflectors—a Composite Chapter

Amateur observers on numerous occasions have testified to the superiority of wooden tubes over metal tubes, in cases where the telescope maker intends to do fairly critical observing with his telescope. Here is some of this testimony; first from the Reverend T. E. R. Phillips, F.R.A.S., and F. J. Hargreaves, F.R.A.S., in comment reproduced from the *Journal of the British Astronomical Association:* "There is a widely held view that reflectors are much inferior to refractors in defining power, assuming equal optical quality, and there can be little doubt that in most cases this is so, especially when the reflector tube is of metal and closed on all sides. Experience over a long period at Headley with an 8" refractor and a 12¼" reflector in an iron tube shows that the number of nights when the image in the reflector is as good as that in the refractor is very small.

"A third instrument at Headley, the Association's 18" reflector, formerly the property of the late N. E. Green, has recently been remounted in the dome formerly occupied by the 12¼", and its performance since remounting is worthy of record insofar as it affects the question of the relative merits of the two types of instrument. Before the remounting, the 18" mirror was carried by a square wooden tube, completely closed on all sides, and the image usually had the well-known reflector characteristics—unsteadiness, lack of crispness, and inability to bear high magnification.

"The sides of this wooden tube were made after the manner of a door, with stiles, rails, and panels. The panels having for the most part rotted, they were removed prior to the re-mounting of the instrument, and it was decided not to close in at once the large openings left by their removal, in order to observe the effect of allowing the air to circulate freely through the tube. In brief, the effect is to remove completely the characteristic defects of the reflector, so far as planetary images are concerned.

"The performance of this instrument has surpassed all expectations—so much so that, in spite of the great disparity of aperture it is now rare to find, on occasions of poor seeing, that the refractor image is steadier or better-defined than that of the reflector.

"It should be understood that no claim is made for novelty in the idea of the skeleton tube, which, of course, is used for all the very large reflectors; it is only desired to point out the very great benefits to be obtained by adopting this type of tube for the smaller instruments, for which it has not hitherto been generally used.

"Experiments have shown that when the external temperature is falling, as of course is the general rule at night, it is impossible to keep the temperature of the air inside a 'closed' tube uniform and equal to that of the external air. An electric blower sending a current of air up the tube is a help in the smaller sizes, but the trouble begins again as soon as the blower is stopped. In the case of a metal tube, the upper wall becomes colder than the lower wall by radiation, thus setting up convection currents within the tube. If the tube is lagged with felt, or if it is of wood, this trouble is

avoided in part, but the tube and the air within it will then remain warmer than the external air during the whole time that the temperature is falling, and for some time after.

"The presence of this mass of relatively warm air can be made visible readily when the conditions are suitable. The telescope should be directed to a bright star and the eyepiece racked out considerably to give a large out-of-focus disk, which will be seen to be irregularly in motion. If an assistant then opens the door near the bottom of the tube and flaps a piece of cardboard vigorously in front of the opening, the out-of-focus disk will "boil," owing to the inrush of the cooler air. The air within the tube can be readily set in rotation by this means, and the rotation is visible in the eyepiece; but no amount of flapping will bring about uniform conditions."

Capt. M. A. Ainslie of the British Astronomical Association writes as follows: "A very noticeable thing about the American instruments is that most of them have metal tubes. Most of our telescope constructors have long abandoned the metal tube for wood, the general experience being that the performance of a reflector in a wooden tube is distinctly better than one in a metal tube. I had at one time a 9″ in a square wooden tube, side by side with an 8½″ in an iron tube, the optical quality being the same in both instruments; but there was no mistaking the superiority of the 9″. The wooden tube, too, was a great protection against dewing of the flat; this took place incessantly in the iron tube, but never in the wooden. It was not uncommon, on a rise of temperature, for the speculum to become dewed in the iron tube: this never happened in the wooden.

"The advantages of using no tube at all, but merely a frame, have long been recognized over here. Such old-time workers as Lassell, De La Rue, Lord Rosse (in the case of his 36-inch), and others, showed long ago that the freedom from tube currents thus obtained was most striking, although one gets nearly the same effect with a *square* wooden tube, owing to the space at the corners which is clear of the entering light.

"A very striking instance of the advantages of doing away with the tube has recently been afforded here in the case of an 18″ reflector belonging to the 'B. A. A.', and now at the observatory of the Rev. T. E. R. Phillips, whose name will be familiar to you as that of a very well-known planetary observer, and a leading authority on Jupiter. He has had for many years an 8″ Cooke refractor and a 12¼″ Calver reflector, both under domes and in iron tubes. He found that he hardly ever used the reflector on Jupiter or Mars, because the 8″ refractor invariably gave a sharper and far steadier image; and when he first mounted the 18″ reflector in its wooden tube out of doors, although its performance was pretty good, the 8″ was still better.

"However, he removed the 12¼″ reflector from its mounting, and mounted the 18″ in its place, cutting away the sides of the tube so as to leave virtually a mere framework. The effect, to use his own expression, was absolutely 'startling'. The 18″ at once surpassed the 8″, and is now his regular working instrument under all conditions.

In "The Splendour of the Heavens" Capt. Ainslie recommends that the

inside diameter of the tube be a full inch greater than that of the mirror, because most of the air currents inside the tube tend to hug the sides.

In Figure 1 the late Charles W. Ingalls showed one way to saw out the staves for a hexagonal tube on a fine circular saw. Make the triangles of the guide by very precisely copying in wood a 30-60-90-degree standard triangle,

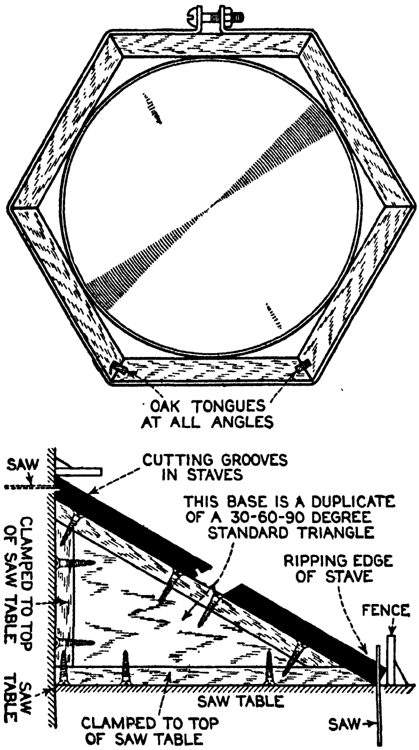


FIGURE 1

he advised. For the staves use about ¾-inch stock. Groove the edges $\frac{3}{16}$-inch wide and ¼-inch deep and set the slip-tongues in white lead. In the second drawing two positions of the guide are combined in a single sketch, for convenience. That is, in order to obtain the other aspect, turn the page sidewise.

Horace E. Dall writes: "Regarding square wood tubes versus round metal ones, even my limited experience has shown how clearly is the superiority of the former, that I am rather surprised that the American amateurs haven't

noticed it to speak of. I am speaking of moderate or large instruments and I have studied and experimented with tube currents in both kinds quite a lot, also currents induced by the presence of the body of the observer.

"The latter point seems to have been practically ignored in the Springfield mounting, where the observer sits practically under the mouth of the tube, and a goodly column of warm air is certain to intersect the beam about to enter the tube. Skeleton tubes also suffer from this defect as well as giving dewing troubles if in the open. I have experimented with electric fans and so on but find the best solution is the well insulated tube of ample dimensions (including length). It seems to me the Springfield might be much improved by extending the tube—the balance weight thus be reduced—or at least one component of it."

A. V. Goddard, of Portland, Oregon, reported as follows, with regard to the use of a fan in connection with his 16" reflector which has a door just above the mirror:

"I read of some experiments by Professor W. H. Pickering with a fan, so I decided to give it a trial. I purchased a small 6" electric fan and attached it direct to the tube so it would blow in through the door. But the slight vibration of the fan was so magnified in the eyepiece that the idea seemed impracticable. I then secured the standard for a music rack and made a separate mounting for my fan, also in order that I could raise it or lower it and set it at any angle. When I first tried it, a friend who was not accustomed to looking through a telescope happened to be calling, so I asked him to look at Jupiter. Only about three of Jupiter's belts were visible—until I turned on the fan. Then he said, 'Why, that makes a *great* difference. I can see 100 percent better.'

"The effect was like blowing away a fog, and the detail, even with 600 diameters, was very clear. Since then, I have found the fan so far ahead of any other method that I always use it."

Not all of the above testimony is in mutual agreement: circumstances vary and, further, many of these things are a matter of opinion. What is sauce for the goose may be ipecac for the gander. It does seem, however, that, after making a fine mirror which deserves the best chance it can be given, the question of using it to best advantage should be considered.

Dealing with Spider Diffraction

By A. Couder, Astronomer at the Observatory of Paris

[Editor's Note: When prominent stars are viewed or photographed with reflecting telescopes having secondary mirrors or diagonals supported by spiders, the diffraction around the spider legs or secondary supports adds to each star a number of points or spikes, depending on the number of legs past which the incoming light must pass. Some non-astronomical persons are said to believe the stars actually have such spikes on them—would a star not *have* to be star-shaped? As long as the obstruction exists the diffraction will of course exist also and cannot actually be annulled. One way, however, to render it at least inconspicuous is by spreading it around the field. The note which follows explains how this may be done efficiently, should it prove desirable to do away with the spikes. The original article appeared in *L'Astronomie* (Bulletin of the Astronomical Society of France), January 1934, and was translated by the editor, who acknowledges kind assistance over two hard spots, given by C. J.—or rather, by C. J's. teacher of French when C. J. was stumped.]

At the first glance one can recognize celestial photographs made by means of a reflecting telescope: the images of very brilliant stars are ornamented with long slender arms at right angles. Is it significant to mention here that this appearance is due to diffraction of the light; that it is manifest each time that the bundle of rays used is limited by an outline which is partly made up of straight lines; that this effect must be ascribed to the metal strips at right angles, which support the secondary mirror in the interior of the telescope tube?

The presence of the arms is sometimes useful. While feeble stars produce little black spots on the plates, the position of which may easily be determined within about one micron, the very brilliant stars form diffuse spots, sometimes enormous, and it would be difficult to locate their center if it were not indicated by the arms which radiate from it. After taking certain precautions, the point of the arms makes it possible to determine the position of a brilliant star with the same precision that is possible with that of a faint star.

Except in such cases one would, however, like to remove these luminous appendages from the images. This sometimes becomes even necessary when, because of the way the telescope is built, their position-angle cannot be altered, and one of the rays from a brilliant star obscures an interesting object.

The secondary mirror of the 0.80-meter telescope is carried by crossed steel strips 2½ millimeters thick, placed diagonally across the tube, which is square. The position-angles of the arms are ± 45° and ± 135°. In 1932, the companion of Sirius came very precisely under one of the arms of the principal star. M. Danjon, hindered in the observations which he was making on this little star by this unfortunate conjunction, suppressed the arms by the following means:

He masked the crossed obstructions which caused them, by placing in front of the telescope a diaphragm pierced by four identical openings of elliptical form *A*, as in Figure 1, at the left, each being inscribed in the space between the arms which support the secondary mirror. By this artifice the observation of the Companion became easy, and Mr. de Kerolys was even able to photograph it. The loss of light which resulted from the use of this diaphragm with elliptical holes is less than one would at first think; it is only 20 percent, or at worst a quarter of a magnitude.

I have sought to make this loss still smaller by means of a wrinkle which differs a little from the one described, but is practically the same, at least for one particular purpose: photography at the Newtonian focus.

To each of the four arms *ae* (Figure 1, left) which support the secondary mirror *m*, one may attach a little screen formed of a sheet of metal whose outline is obtained by constructing on the length of the arm *ae* (Figure 1, right) a sector *abcd*. The portion *bcd* is moved to position *b'c'd*. The other half of the outline is drawn symmetrically relative to *ae*; $c'c''$ is made to measure about three fourths of *bb'*. The four screens being in place, one observes that the outline which limits the bundle of incident rays consists of four circles, to wit: the outline of the large mirror and that of the secondary, plus the two circles which are made in making a suitable change in position of the arcs which limit the spindles.

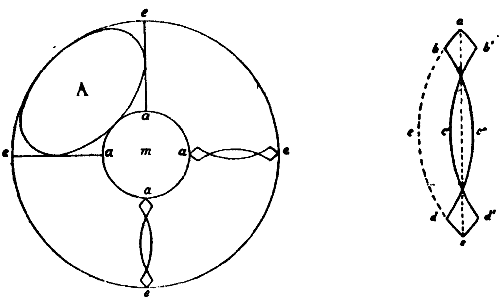


FIGURE 1

The light intercepted is a total of 4 percent of that which would be available without the screens. The presence of these screens obviously modifies the diffraction figure, which is no longer identical with its normal form (Airy figure). We are not here considering the effect that is produced in the central region of this figure; we merely say that the brightening of the central spot and of the first ring presents little variations with four-part symmetry, but the pattern of the plates is too coarse to permit the effect of this modification to be perceived on the scale obtained at the focus of a parabolic mirror of $f/6$. What is interesting is that, from some hundredths of a millimeter to some millimeters from the center of the image, the brightening presents a symmetry of revolution which is practically perfect.

Here is the result observable on the photographs (Figure 2). The appearance of faint stars is not modified. Stars sufficiently brilliant to show, in the absence of spindles, a deformation which reveals the four-part appearance of the arms, now preserve a perfectly circular form. Their diameter is increased several percent of their value, but the image is very openly terminated, and the precision of points of position is considerably increased. Finally, the very brilliant stars, which would have arms several millimeters

FIGURE 2

long, are completely freed from them. As a result of photographic diffusion they have the blurred appearance of a comet minus its tail. For these stars, which furthermore are not numerous, measurements of position become inexact, since one can no longer use the arms.

The use of spindles establishes a perfect continuity in the variation of aspect of the photographic image, in proportion to the brightness of the star which produces it. This, it seems to me, appears to offer some interest in connexion with photographic photometry.

The Richest-Field Telescope—a Plea for Low Magnification

By S. L. Walkden
London, England

[Editor's Note: A Richest-Field Telescope, or "R.F.T.," is one which, after calculated design based on several determining factors, shows the greatest possible number of Milky Way stars at one view. Its purpose is to afford spectacular views of the heavens—lending itself well to use by those of the amateur's visitors who have been led to expect sensational views through his telescopes and often have gone away disappointed at what they saw because in seeing they saw only with their eyes; also lending itself to his own uses for Milky Way study. Its emphasis is on low power.

Almost any low-power, short-focus telescope, from a common binocular up, will give striking views of the heavens. One thing Mr. Walkden, the author of the following discussion, did was to see that a special circumstance —the fact that at the 11th magnitude star density ceases to increase exactly at the round rate of 2½ times per magnitude, permits the design of a special telescope to make visible at one view the largest number of galactic stars. As each observer's pupilar opening may be expected to have a different diameter, the exacting designer may even, if he wishes, work out R.F.T's. for his own eye.

The chapter which follows is a composite of several items: the first is a reprint of the paper in which Mr. Walkden originally proposed the idea—in *Knowledge,* now *Discovery,* 1916. Other pertinent items follow.

"My chief part," he writes, in reply to a question directly asked him by the present writer, "was in perceiving and publicly pointing out how *every* aperture could be made 'a' R.F.T., of that aperture, for a given observer and that there was *one* of all these which, in connection with the curve of star density against magnitude of stars, was uniquely 'the' R.F.T. for the observer, in respect of maximum countable number of stars per apparent square degree."]

From *Knowledge:*

Many users of telescopes have probably experienced their most exalted feelings of admiration of the heavens while sweeping aimlessly, with low powers, in the region of the Galaxy. The author has himself done so, and has thereby been led to speculate regarding the richest-field telescope, or telescope which, in an average random setting—preferably upon a galactic region—will show through its eyepiece the greatest number of distinct star images. It was therefore with feelings of pleasure that Messrs. Chapman and Melotte's Greenwich table of numbers of stars of various magnitudes in galactic regions was read on page 305 of *Knowledge* of last August;* for, as will be seen, it supplied the very data required to give a practical turn to the speculations referred to.

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* "Last August" refers to August 1914, not 1916. This article was written and placed with *Knowledge* in 1914, soon after reading the page 305 referred to, and about two years before the appearance in print.—S. L. W., 1936.

It is easy to show that the richest-field telescope is that for which Δ/a^2 is a maximum, where Δ is the star density per square degree for all stars down to the faintest, just visible with the telescope, and a is the aperture in inches. In the information it gives, however, a tabular method of calculation has great advantages over calculations of merely critical conditions.

In the table the first column states star magnitudes from the 5th down to the 17th. In the next column, headed "Light of Star," the 17th magnitude star is obviously taken as the unit of light, the brighter magnitudes being then 2.512^1, 2.512^2, 2.512^3, and so on, times brighter than that unit. This 2.512 is the usual light-ratio of magnitudes, or $\sqrt[5]{100}$, for which reason the significant figures are seen to repeat themselves every five magnitudes. In the next column, headed "Aperture in Inches," the standard assumption is seen to be made that the 9th magnitude star is just perceived through a 1″ instrument, and the apertures for the other magnitudes are made to vary from that unit aperture inversely with the square root of the numbers printed in the preceding "Light of Star" column. That gives the accepted aperture values, though it underestimates the apertures for very faint stars, through not allowing for excessive light-absorption in very thick lenses.

The fourth column, headed "Richest-Magnifying Power," requires a somewhat lengthened explanation. Let us take the 13th magnitude 6.31″ telescope, and let us fit it with an eyepiece magnifying 315 diameters (50 per inch of aperture), and having an *apparent* field of view of as much as 50° diameter. If we direct that instrument at random, even near the Galaxy, the average display will be found hardly so good as three stars, *looking* like 4.7 magnitude

Magnitude of Star	Light of Star	Aperture in Inches	Richest Magnifying Power	Objective Field's Diameter (degrees)	Objective Field's Area (sq. degrees)	Total Stars Down to Given Mag. per sq. degree near Galaxy
Col. (1)	(2)	(3)	(4)	(5)	(6)	(7)
5	63100.000	0.159	0.539	92.8000	6760.0000	0.027
6	25120.000	0.251	0.852	58.7000	2707.0000	0.102
*7	10000.000	0.398	1.349	37.0700	1079.0000	0.359
8	3980.000	0.631	2.138	23.3700	429.0000	1.160
9	1585.000	1.000	3.390	14.7600	171.0000	3.510
10	631.000	1.590	5.390	9.2800	67.6000	9.770
11	251.200	2.512	8.520	5.8700	27.0700	25.400
12	100.000	3.980	13.490	3.7070	10.7900	61.700
13	39.800	6.310	21.380	2.3370	4.2900	141.000
14	15.850	10.000	33.900	1.4760	1.7100	306.000
15	6.310	15.900	53.900	0.9280	0.6760	631.000
16	2.512	25.120	85.200	0.5870	0.2707	1245.000
17	1.000	39.800	134.900	0.3707	0.1079	2399.000
*For naked-eye "telescopes":						about
6.36	18200.000	0.295	1.000	50.0000	1962.0000	0.160

Magnitude of Star	Number of Stars Visible in Field	Stars per Mag. Step per Sq. degree	Stars per Mag. Step seen per View	Sum of last column to Given Mag. (Light Units)	Mean Light of Visible Stars (Light Units)	Apparent Mag. of the Mean Star (about)
Col. (1)	(8)	(9)	(10)	(11)	(12)	(13)
5	182.4	0.027	162.4	....	....	....
6	276.0	0.075	202.9	....	....	....
*7	387.5	0.257	277.5	642.8	1.660	5.8
8	497.5	0.801	343.6	986.4	1.983	5.6
9	600.0	2.350	401.7	1388.1	2.330	5.4
10	660.0	6.260	423.1	1811.2	2.746	5.3
11	687.5	15.630	423.2	2234.4	3.252	5.1
12	666.0	36.300	392.9	2627.3	3.945	4.9
13	604.8	79.300	340.0	2967.3	4.910	4.6
14	532.2	165.000	282.3	3249.6	6.210	4.4
15	426.6	325.000	219.6	3469.2	8.140	4.1
16	337.0	614.000	166.1	3635.3	10.790	3.8
17	258.9	1154.000	124.6	3759.9	14.520	3.5
*For naked-eye "telescopes":						
	about			about		about
6.36	315.0	....	....	450.0	....	5.9

This table has been calculated with sufficient accuracy by means of a slide-rule. The zeros added to preserve the appearance in print are not intended to imply accuracy beyond the third significant figures.

stars, but really of 11.3 magnitude, arranged, probably, in an open equilateral triangle.[1] To improve the richness of this field we shall have, of course, to use lower and lower powers, under which treatment the original triangle, while remaining perfectly distinct, will shrink in apparent size; and other stars will pass into view through the edges of the field, so as to increase the total number visible, at one setting, inversely with the square of the magnifying power. That increasing richness of field continues till we have reduced the magnifying power to 21.38 (or 3.39 per inch of aperture); but less than that we must not go, for the important reason now to be explained.

When the given telescope is pointed at a star, the star sends into the telescope a cylinder of light 6.31" in diameter, and, in accordance with the well-known property used in a common way of finding the magnifying power, the 315-power eyepiece reduces that large cylinder of light into one only (6.31 ÷ 315), or 0.02" in diameter. This small cylinder, though only one

[1] Found thus: A magnifying power of 21.38 (fourth column) shows 604.8 stars (eighth column), so a power of 315, with its smaller area of field, shows $(21.38/315)^2 \times 604.8$, or 2.78 stars. These are of 4.6 magnitude (thirteenth column). When there chances to be the nearest whole number—3—of *equal* stars, the probability is that these will give the same total light, and so be of the slightly fainter 4.7 magnitude.

fiftieth of an inch in diameter, contains all the original light less a negligible optical absorption, and easily enters the observer's eye. It easily enters the eye, because *in very dull light* the pupil is as much as 0.2953″ in diameter. But when we have reduced the magnifying power so low as 21.38, we have raised the diameter of the eyepiece's emergent cylinder of light up to (6.31 $\div$ 21.38), or exactly 0.2953″; so that, if we were to use a lower power, the emergent cylinder would become *too large to enter the eye.* Only the center of the object glass would then be in use, and the instrument, instead of being the intended 6.31″, would convert itself into *optical identity* with a smaller instrument on the list. The richest-field arrangement of telescopes of given apertures therefore consists in providing each one with a magnifying power of exactly the aperture in inches divided by the 0.2953″ diameter of the pupil of the eye. Accordingly, that is the quantity printed in each line of the fourth column of the table.

The 0.2953″ diameter of the pupil of the eye—the author's eye, but presumably an average one—is 7.5 millimeters, and was measured in the following way. A very small gas jet at one end of a room was viewed from the other end through one eye. A strip of paper, tapered from a width of five millimeters at one end to ten millimeters at the other, was then passed in front of the eye till the width was found that could prevent the gas jet being seen. That width, 7.5 millimeters, was reasonably presumed to be the exact diameter of the pupil when fully expanded in a very dim light. Calculated in the table as a "telescope" of 0.2953″ aperture, the naked eye, on the basis of 1″ aperture showing a 9th magnitude star, shows stars as faint as the 6.36 magnitude (see foot of table). This agrees well enough with keen-sighted authorities.

To see as many stars as possible at one observation, we naturally require the eyepiece to have as large an apparent field as possible, consistent with satisfactory definition. As well-defined apparent fields of upwards of 50° are now attainable in modern eyepieces, that figure has been adopted; and it has been divided, in each case, by the magnifying power, to give the fifth column's "Objective Field's Diameter," or the degrees diameter of the circular portion of the sky, which is being magnified by the telescope into appearing 50° in diameter. These diameters squared, and then multiplied by $\pi/4$ (which is 0.7854), then give the areas of the objective fields of view, in square degrees, as printed in the sixth column of the table.

The important figures of the next or seventh column, stating the total number of stars per square degree of galactic regions down to the given magnitudes, are taken straight out of Dr. Crommelin's interesting article before referred to.

Since—taking an example—the 9th magnitude 1″ telescope has an objective field area (sixth column) of 171 square degrees, and since all stars down to those it just makes perceptible have a density of 3.51 per square degree (seventh column), it is clear that that telescope shows 171 $\times$ 3.51, or 600, stars at one average view. The corresponding products of the sixth and

seventh columns are therefore written in all the lines of the eighth column, headed "Number of Stars Visible in Field."

Inspection of this eighth column at once tells us that the richest-field telescope which we set out to discover is no more than a modest 2½″ one; for a *larger*, as well as a smaller, one actually shows a less number of stars in its field of view at one average observation. It should certainly be an acceptable encouragement to owners of the manageable two- to three-inch instruments to know that in at least one respect they have a unique advantage over those who only possess the giants. The advantage is naturally one that is most useful in studies relating to stellar groupings, or finding comparison stars, or where, as intimated before, the observer is only taking a pure delight in admiring the heavens in as *wholesale*, beautiful, and comprehensive manner as possible.

Now although, according to the precise measure adopted, the 2½″ telescope is the richest-field one, and should, before all others, be so called, yet, even in the precise sense, the 6″ telescope is little inferior, while in most opinions the display in the larger instruments is decidedly more attractive and "richer." This is apparently because most eyes esteem a considerably brighter appearance of the individual stars more than a small loss in the number visible at one setting. Since we are dealing here with matters of taste—some admire one Sirius-like star, where others prefer the same light distributed over a hundred fainter stars—we cannot again set up precise criteria. Nevertheless, as it seems likely enough that the artistic richness of the field is partly connected with the total light thrown into the eye by the stars whose images are distinctly perceived, the tabular calculations have been continued with that probability in view, although with no intention of detracting from the more precise and more serious conclusions reached in the eighth column.

In the seventh column we read that down to the 17th magnitude there are 2,399 stars per square degree of sky, and down to the 16th magnitude 1,245 stars per square degree. The difference of these numbers, or 1,154 in the ninth column, is evidently the number of stars of between the 16th and 17th magnitudes per square degree of sky. Similarly, 614 in the ninth column, being the difference between the numbers 1245 and 631 in the seventh column, is the number of 15th to 16th magnitude stars per square degree of sky, and so to the top of the ninth column. It will be seen that the ninth column is suitably headed Stars per Magnitude-Step per Square Degree of Sky.

In the tenth column the figure 124.6, being the product of 0.1079 in the sixth column and 1,154 in the ninth, is plainly the number of 16th to 17th magnitude stars perceived at one view through the 17th magnitude, 39.8″ telescope. Similarly, 166.1 in the tenth column, being the product of corresponding figures in the sixth and ninth columns, is the number of 15th to 16th magnitude stars seen at one view in the 16th magnitude 25.1″ telescope; and so on to the top of column 10. The figures of this tenth column are seen to have a maximum; but that cannot be shown to demonstrate anything more important than that the 10th to 11th magnitude stars contribute most

of the starlight in any telescopic view of the heavens—a fact already well known.

The next column, the eleventh, in which the interest again increases, requires a little concentrated thought if what it signifies is to be understood. As already explained, the figure 124.6 at the bottom of the tenth column tells us that there are those many 16th to 17th magnitude stars visible at one average observation with the 17th magnitude, 39.8″ telescope. Now these stars are at the limit of visibility through that telescope, so that if we adopt as our light-unit the light received by the eye from a star apparently at the limit of visibility (a unit of obviously the same value with the naked eye as with *any* telescope), we see that with the 17th magnitude, 39.8″ telescope, the 16th to 17th magnitude stars seen in one observation send into the eye 124.6 units of light. Just in the same way, the 16th magnitude, 25.1″ telescope, sends into the eye 166.1 of the same just-visible units of light, and so on up to the top of column 10. But what light units do the 15th to 16th magnitude stars, visible in the *17th magnitude 39.8″ telescope,* contribute to the eye? That is what we must proceed to find.

The number 166.1 in the tenth column represents, as stated, the light units contributed by the 15th to 16th magnitude stars seen at one observation with the 16th magnitude telescope. If we now look through the 17th magnitude telescope, the same stars will, *if all seen,* contribute more light in the ratio of the areas, or the squares of the diameters, of the apertures; so that the figure 166.1 becomes $166.1 \times (39.8/25.1)^2$, or 418 units of light. But, owing to the reduced field of view of the larger telescope, a proportionally less number of stars is visible at only one view; so, multiplying the 418 units by the ratio 0.1079/0.2707 taken from the sixth column, we find that the 15th to 16th magnitude stars *seen* contribute only 166.1 units of light in the 17th magnitude telescope—just what they did in the 16th magnitude one, and would do in an 18th or 19th magnitude one. There is no coincidence in the figures: the correction for the number of stars seen is necessarily the reciprocal of the correction for the light contributed by each star; one (the latter) is the ratio of the apertures squared; the other is the *inverse* ratio of the apertures squared, and so they cancel each other—that is all.

Since, therefore, the numbers down the tenth column represent alternatively the light-units contributed by the various magnitudes of stars in a view through the 17th magnitude telescope, the sum of all those numbers, which is the 3759.9 at the bottom of the eleventh column, is the *total* light-units contributed by *all* stars distinctly seen at one average view through the 17th magnitude telescope. Similarly, the sum of all the tenth column down to the last line but one—3635.3 in column 11—is the total units of light contributed by all stars distinctly seen at one average view through the 16th magnitude telescope, and so on.

The eleventh column may disappoint in having no maximum, but at about the 14th magnitude (10″) telescope it shows so great a falling off in the rate of increase as to enable us to say that, *judged by the total starlight sent into the eye at one average view,* the richness of field of only a 10″ telescope is

not very greatly inferior to that of the 40″ Yerkes instrument, even when no allowance is made for the absorption of light in the very thick lenses of the latter instrument.

However, many may not agree that the total starlight per field of view is a proper measure of the richness. For example, the 3249.6 units of light of the 10″ telescope may be supplied either by 3,250 just-perceptible, glittering points of light, like sparkling dust, or by 20 objects *looking* like 1st magnitude stars; and which is the "richer" field it is hard to say. These considerations suggest that the eye incorporates a measure of richness based on the light-units contributed per star visible. Those quantities are easily found by dividing the figures of the eleventh column by those of the eighth; but as the number of light units in each average star visible does not readily convey its import, the corresponding ordinary star magnitudes have been calculated by logarithms, assuming, as before found, that our light-unit—the star just perceptible by the eye—is always of apparent magnitude 6.36. The magnitudes so found are printed down the last column.

As showing the comprehensiveness of the information respecting star fields that is provided by the table, it may suffice to go through the example of the 2.51″ telescope, column 3. From column 1 we read that the instrument just shows 11th magnitude stars, which—see column 2—have 251.2 times the light of the 17th magnitude stars, just visible in the 39.8″ or 40″ Yerkes instrument, columns 1 and 2. We then read that the 2.51″, when provided with its richest-field, or lowest, 8.52-power eyepiece, column 4, having a largest practicable objective field of 5.87° diameter, column 5, and 27.07 square degrees area, column 6, shows an average of 687.5 stars in its galactic field of view, column 8. We next read that these stars send through the telescope and into the eye a total light equal to 2234.4 just-visible stars, column 11, the same as if the 687.5 stars were all composed of stars appearing as 5.1 magnitude stars do to the naked eye, column 13. By way of addendum, if we wish to compose the real probable field, we can easily do so by first charting down on a 10″ paper disk, held 12″ from the eye (apparent field then about 50°), 423, column 10, just-visible stars, as if they were 6.4 magnitude naked-eye stars; then 423.1, column 10, divided by 2.512, column 2, or 168 stars, one magnitude brighter, as if they were 5.4 magnitude naked-eye stars; then 401.7, column 10, divided by 6.31, column 2, or 636 stars, as if they were 4.4 magnitude stars, and so on, step by step from the *bottom* of column 2 as we step up from the proper line in column 10. The reasons for this method are more prolix to explain than they should be simple to discover.

It will be noticed that the top of the table tacitly assumes that all stars brighter than the 5th magnitude are not brighter than the 4th magnitude; but when that convenient assumption is not made, the figures are substantially unaltered, because of the comparative rareness, telescopically, of stars brighter than the 4th magnitude. A correction to the areas in the sixth column, to allow for large areas of sky being sensibly spherical instead of flat, is also not made. This correction being, however, only a five percent reduction for

the top figure, two and a half percent for the next, one percent for the third, and practically nothing after that, is dismissed as of no account.

To conclude, the most important fact established is that, for sweeping in galactic regions, the richest-field telescope, showing the observer the greatest number of distinct, telescopically lucid star images at one average view, is only a 2½″ telescope; and it does its best in that respect when fitted with an eyepiece, magnifying only 8½ times, designed to have a field of view as large as possible.

Note, added 1936: The Chapman & Melotte data of column 7 is perhaps a little ancient, and I should like sometime to recalculate on modern revisions. I think on such later data *the* R.F. aperture may be found an inch or two larger, and that the crowding of the fields of view of the larger sizes may fall away a little more rapidly. I also think that if *the* R.F.T. size were determined separately for the Cygnus region (where the galaxy is near) and for the Scorpio region (where the galaxy is far away) the size might be a few inches larger for the Scorpio region and the fields a little more crowded and more splendid; but I am not at all certain about these details, which might well be made matters of special research.

[EDITOR'S NOTE: Further communications regarding the R.F.T., by Mr. Walkden, appeared in *English Mechanics,* May 21, 1920, page 201, under the title "Small Telescopes for Stars," and October 10, 1930, page 673, and in other places but these add little to what is told in the present chapter. The latter of the two had been seen and saved and, just as an invitation for him to write further on the subject was being prepared, a new article by him appeared in *Popular Astronomy* (March 1936), which thus scored a "scoop on us." That article develops the subject from a rather fresh angle—that is, through the algebraic route which many are believed to prefer, hence it also is reprinted here by kind permission of the editor of that magazine.

It may save the reader some confusion and backtracking if it is pointed out early in the chapter that there are two separate concepts to be kept distinct from one another, all through the discussion—what the author calls *a* R.F.T. and what he calls *the* R.F.T. When he mentions *a* R.F.T. he means a telescope which shows the greatest number of stars for its particular aperture, but *the* R.F.T. refers to that particular one of the several aperture sizes which gives the richest-field view of all. Sometimes it has been convenient to call the latter the R.R.-F.T., in an abbreviation of obvious meaning.]

From *Popular Astronomy:*

A time when discoveries with large telescopes overshadow much that can be done with small ones would seem to be the time when anything in which small telescopes excel should be rescued from oversight. Now there is one curious and pleasing thing in which small telescopes of about 3 inches aperture do excel, and that—surprising to many who first hear of

it—is in being able to show *more* stars in the average Milky Way view than any smaller or *larger* telescope can show.

In one way of explaining this, suppose we make a telescope to reveal stars down to a certain magnitude m, and therefore one to be called an mth-magnitude telescope. Using as symbols—

A for the apparent average star-density in the eyepiece, or number of stars per apparent square degree of area of the field of view,

Δ for the actual average star-density in the sky down to the magnitude m, that is for the number of stars down to magnitude m per square degree of area of the actual sky, and

M for the magnifying power;

then it should be evident enough that

$$A = \Delta/M^2; \tag{1}$$

on which account we could make the field look as crowded as we liked, by using a lower and lower magnifying power, if it were not for an important limit now to be explained with the aid of three further symbols—

a for the aperture diameter in inches, which the observer needs and uses to see clearly the mth-magnitude stars,

d for the inches diameter of the Ramsden circle or exit pupil, through which the light of the object glass emerges from the eyepiece, and

e for the inches diameter of the pupil of the observer's eye in the dark.

With any telescope it is an inevitable optical rule that $d = a/M$, so that as M is lessened d enlarges. But directly d commences to exceed e, as it must do when M is less than a/e, some of the light of the telescope fails to enter the eye. That makes the faint stars of actual magnitude m disappear, and therefore makes the mth-magnitude telescope cease to exist. Therefore, substituting a/e for the lowest and richest M in (1), we have for the mth-magnitude telescope—

$$\text{Utmost } A = e^2 \times (\Delta/a^2) \tag{2}$$

Using as a further symbol—

k for the inches aperture diameter with which the observer sees 9th-magnitude stars, we know that, because stars are 2.512 times fainter per magnitude,

$$a^2 = k^2 \times 2.512^{m-9} \tag{3}$$

and substituting this for a^2 in (2), we have for the mth-magnitude telescope—

$$\text{Utmost } A = (e^2/k^2) \times (\Delta/2.512^{m-9}) \tag{4}$$

Therefore, because e^2/k^2 is a constant, Utmost A increases for increasing magnitude telescopes, so long as Δ increases faster than 2.512^{m-9} increases with increase in m; and it reaches its maximum at that magnitude of star and telescope where Δ ceases to increase at a faster rate than the 2.512 times per one step in magnitude at which the 2.512^{m-9} continually increases.

According to good tables of star-density, like the Chapman & Melotte tables for the zone of the Milky Way, Δ ceases to increase faster than 2.512 times per step in magnitude just at the 11th-magnitude stars. There-

fore the 11th-magnitude telescope exhibits the maximum Utmost A, and therefore it is the richest-field *size* of Telescope. For very keen-sighted observers k is as small as 1.00 inch, in which case, from (3), $a = \sqrt{(1.00^2 \times 2.512^{11-9})} = 2.512$ inches, or say 2.5 to 3 inches aperture for ordinary observers. For an observer with an eye pupil with e as great as 0.30 inches in the dark, the richest-field magnifying power with this telescope, or a/e, is then as low as 2.512/0.30, or 8.4. Then, by (4), utmost $A = (0.30^2/1.00^2) \times (\Delta/2.512^{11-9}) = 0.01426 \times \Delta$; and Δ being 25.40 for the 11th-magnitude stars according to good star-density tables, this observer's maximum utmost $A = 0.3622$, meaning 362 stars visible per 1000 square degrees of the apparent field of view. Of course with a modern eyepiece field appearing 50 degrees in diameter, and so of $50 \times 50 \times 0.7854$, or 1964 square degrees area, the number of stars in the average Milky Way view can be as high as 711.

The conclusion that the richest-field telescope is of the size corresponding to the magnitude of stars where the stars increase in numbers just as fast as they decrease in brightness, holds firm; but too much precision and other things should not be read into the further conclusions. Tables of star-density still differ as to the exact magnitude at which the stars increase in number 2.512 times per step in magnitude, some tables placing it nearer the 13th than the 11th magnitude. That would make *the* richest-field size of telescope nearer 7 inches than 3 inches, with a richest-field magnifying power of about 24. Then it needs considering that, while the utmost apparent star-density declines rather gradually in the views with the larger telescopes, the proportion of strikingly bright-looking stars increases rather rapidly and the proportion of faint-looking ones decreases rather rapidly; so that, except in actual number of stars to be counted, the fields of the larger telescopes generally *look* richer, and decidedly more splendid.

It is not easy to arrange an ordinary long-focus 2.5- to 3-inch astronomical telescope as the richest-field telescope, because of the large size of the 9- to 10-power eyepiece needed; but it is easy enough when an object glass of focal length only about 5 to 6 times the aperture is employed. Several of the best optical manufacturers of the world are already listing small, low-powered, short-focus telescopes which are practically richest-field telescopes; and with them most beautiful views may be obtained of the star clouds of the Milky Way, especially of those star clouds near the constellations of Cygnus in the north and Scorpio in the south.

One other formula for utmost A may be given in conclusion. Calling the 9th-magnitude star just visible with k^2 area of aperture the star of unit brightness or illumination, and using—

i for the brightness or illumination of the star just perceptible with aperture area a^2, then evidently—

$$a^2/k^2 = 1.00/i, \text{ or } a^2 = k^2/i, \tag{5}$$

which, inserted for a^2 in (2), renders us for the mth-magnitude telescope

$$\text{Utmost A} = (e^2/k^2) \times \Delta \times i \tag{6}$$

This (6) corresponds to (4), for i is the same as $1/2.512^{m-9}$; but (6) is a form that avoids the magnitude convention, and therefore in some opinion

makes it plainer how the maximum utmost apparent star-density, *A,* for the richest-field telescope, occurs for the stars and telescope corresponding to where Δ, the star number, ceases to increase faster than *i,* the star's brightness, decreases; or, in other words, where the stars down to one percent fainter are precisely one percent more numerous.—*London, England.*

[EDITOR'S NOTE: From personal communications from Mr. Walkden some further notes and comments have been selected as being likely to help.]

By Mr. Walkden: The conclusions can be given practical application, for those who wish thoroughly to enjoy rich-field observation. Suppose an amateur already has a telescope of, say, 6″ aperture, and wants to turn it into a 6″ R.F.T. He may have some customary battery of eyepieces of powers like 400, 200, 100, and 60, the last being called his "low power," obviously of 10 per inch of aperture. That eyepiece may give him what he considers very fine views of the Milky Way, on which he sometimes relaxes from the high-power work he may just a little too much regard, but those views should only whet his appetite for much better obtainable views.

What he needs to do, is to procure an eyepiece magnifying only about 3.5 per inch of aperture, which of course will be a power of only about 21 for his telescope, since $6 \times 3.5 = 21$. That means obtaining from the makers an eyepiece of focal length $1/21$ of the focal length of the object-glass or mirror; so if the object-glass has, as likely enough, a focal length of about 12 times its aperture, or $12 \times 6''$, or 72″, there must be obtained an eyepiece of about 72 divided by 21, or 3.4″ focal length.

The eyepiece had better be required to have an apparent field of view about as wide as 40°, and it is advisable to have it of the positive or Ramsden type, and not of the negative or Huygenian type, because the Ramsden more easily has a wide field of view coming sharply to focus from center to edge, as is mentioned by Mr. H. A. Lower of San Diego in a private communication which I have been permitted to read.[2]

Then another point: in order that the eyepiece should not miss showing faint stars towards the edge of the 40° apparent field of view, it is needful that the field lens of the Ramsden eyepiece of average type should have a diameter of about the focal length of the object-glass divided by the aperture, and again divided by five, and then plus one-tenth of an inch. Or, in symbols, the diameter of the field lens should be about $(f/a)/5 + 0.10''$. With this 6″ telescope that will be $12/5 + 0.1$, which is about 2.5″.[3] If that is

[2] Letter to Mr. A. G. Ingalls—"The low power telescope would, I think, open up a field which is new to most amateurs. The power must be low. Many beginners have a high power complex and it is difficult to convince them that low power is worth much. One thing we have found through some of our experiments is that low power Huygenian oculars are *no* good for this low power, wide field work."—H. A. L.

[3] It is easy to see that 40/M is the degrees diameter of the *actual* field. That, in the R.F.T.'s is 40/3.5 *a* degrees in diameter. The *inches* diameter of the corresponding focal image which the field lens must accept is 40/3.5 *a* of $f/57.3$, where the $f/57.3$ is the inches length of a degree in the focal image. That is the $(f/a)/5$ of the formula for the size of the field lens. The 0.10″ is a penumbral extra for the average type of Ramsden. A further penumbral extra, *inversely* depending on the aperture, is neglected because usually so small, but it calculates at about $(f/a)/50.a$, or $f/(50.a^2)''$, when it needs noticing for *small* apertures of long focal length. Notice that $f = 5a^2$ makes the eyepiece need to be about as wide as the object-glass.

hard to obtain, then the nearest must be put up with; but, clearly, a great help is to have an object-glass or mirror of quite short focal length, say not over about six times the aperture. Lastly, the eye lens should be amply large enough. Three-quarters the diameter of the field lens will generally do, though sometimes that should be a little exceeded for unusually small and short telescopes.

If the telescope is a reflector, its flat, placed $a/2$ inches within the focus, should intercept a cone of light which has *there* a diameter of $c/5 + a/2c - 0.10''$, where c is the ratio f/a. That will be $12/5 + 6/24 - 0.10$, or $2.55''$ for the $6''$ telescope of the example. The major axis, always practically 1.4 times that minor axis, may then be taken $3.6''$ in the example. The factor 1.4 is simply the square root of 2.

A small reflecting R.F.T. has such a very large actual field and obstructing flat, that it is advisable to make the tube leave clear an internal diameter *expanding* from the mirror by about $1''$ in every $5a$ inches. For the $6''$ aperture example that would be $1''$ per $30''$, which would mean an internal diameter of about $9''$ at the open end of its $7'$ tube.

If in a fresh design of mirror there is some doubt as to what focal length should be chosen to minimize the size and obstruction of the flat, the approximate rule of 1.6 times the square root of the cube of the aperture will usually be found to give a good answer. That will be about $23''$ for the $6''$ aperture, but less than about four times the aperture is seldom advisable if good definition of the marginal stars of the *large* actual field is a consideration. When all compromise becomes difficult for small reflectors of less than $3''$ or even $4''$ aperture, it is better to use instead an object glass, and so a small refractor.

That is about all that is necessary to make the telescope give wide views, as crowded or rich as possible with stars while acting at its full aperture, in fact to make it be *a* Richest-Field Telescope of the $6''$ aperture.

But suppose there is no alterable telescope in possession, the desire being simply to have that telescope which gives as crowded average star fields as possible with any telescope. In this case, strange though it may seem, the right thing is to obtain an object-glass of only about $2.75''$ aperture; and a focal length of only about six times that, or $16.5''$, is recommended. The magnifying power of 3.5 per inch of aperture is again needed, which means 9.63, since $3.5 \times 2.75 = 9.63$. This in turn needs an eyepiece of focal length equal to the focal length of the object-glass, or $16.5''$, divided by 9.63, which comes to $1.71''$. In the few other things to be attended to, the eyepiece again is to have an apparent field of view about 40° wide, and it needs to be of the positive or Ramsden type. The diameter of its field lens should again be about equal to the focal length of the object glass divided by the aperture, and again by 5, and all plus one-tenth of an inch, or $(16.5/2.75)/5 + 0.10$, or about $1.30''$; and that should not be hard to obtain of makers.

As before, the eye-lens should be about three-fourths the diameter of the field lens, or about $0.97''$, and the eye-hole be amply large enough too.

Now that telescope will not only give the most crowded average star-

fields possible with 2.75″ of aperture, but it will give the most crowded average star-fields possible with any aperture whatever. That is to say, beside being *a* R.F.T. of 2.75″ aperture it will be of all telescopes *the* Richest-Field Telescope.[4] The secret is that it is just of the size able to show the magnitude of stars, the 11th, at which the stars stop increasing so fast in numbers as they decrease in brightness. A larger R.F.T. shows fainter stars, but they are not so much more numerous in the sky as to compensate for the smaller actual field of view of the larger-sized R.F.T.

In looking through any R.F.T. a little more than the usual care should be taken to put the eye centrally to the eyepiece, because the Ramsden circle is so exactly the same size as the pupil of the eye. If the eye is not central it cannot receive all the light of the telescope and the appearance of the view is dimmed. It also needs noticing that the Ramsden circle is not unlikely to be a distance nearly ¾″ this side of the eye-lens, or as found by receiving it sharply on a tiny tracing-paper focussing screen. Now the pupil or iris of the eye (just *in* the eye) ought to be just about there—neither nearer nor farther from the eye-lens, if the eye is to see the whole field of view and its stars equally bright all over. So it is sometimes an improvement to have an eye-cup very well shaped, to help the eye to keep its proper place and distance at the eyepiece. These considerations are less important in the ordinary high-powered telescope, because the Ramsden circle and exit beam are so small as to go entirely into the eye, even if the eye is placed almost carelessly at the eyepiece.

There is a rather funny thing about *the* R.F.T. You notice *the* most crowded R.F.T. is at that magnitude of star at which the stars are 2.512 times more numerous per one step in magnitude—assumed, as stated, to be the 11th magnitude, as well as yet known. On the clearest nights and to the keenest sight the aperture indicated is 2.51″. But as mist appears or as the moon rises the aperture for *the* R.F.T. grows, perhaps to 10″ or 12″. And as the sun rises the aperture still further grows, perhaps through 50 or 100 *feet*. So, while *the* R.F.T. *can* be defined as a *magnitude* of telescope, every R.F.T. greater than about 2.51″ aperture *can sometime* become *the* R.F.T., according to the condition of seeing.

All particulars corresponding to the preceding descriptions have been calculated for standard sizes of telescopes, and are shown in the next table.

In the last three lines of the table the perceivable magnitude M is calculated by the easily determined formula $M = 8.80 + 5 \log a$, in which 8.80 is the magnitude which this observer is supposed to perceive with 1″ of aperture. But for the R.F.T. reflectors the less simple formula $M = 8.56 + 5 \log a - n$ has to be employed, because of imperfect reflection, and because of flat-obstruction wasting a small amount of magnitude n. For the *specified* design of R.F.T. reflector $n = 2.5 \times \log\ [1/(0.98 - 0.18/a - 0.49/a^2)]$. The star-density Δ comes from column 7 of the *Knowledge* article's table. Intermediate values can be obtained from a well-drawn curve; but alterna-

[4] The telescope which may be exalted to the title of the Richest Richest-Field Telescope, or R.R.-F.T.

SIZES OF RICHEST-FIELD TELESCOPES

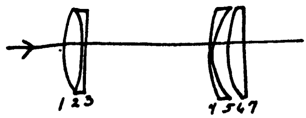
		R.F. REFRACTORS				R.F. REFLECTORS					
	a = Aperture	2″	**2¾″**	3″	4″	**4″**	5″	6″	8″	10″	12″
	F = Focal Length	12″	**16½″**	18″	24″	**16″**	20″	24″	36″	50″	66″
	c = F/a Ratio	6	**6**	6	6	**4**	4	4	4.5	5	5.5
	M = Magnifying Power	×7	**×9.63**	×10.5	×14	**×14**	×17.5	×21	×28	×35	×42
	Diameter of Image (for 40° apparent field)	1.2″	**1.2″**	1.2″	1.2″	**0.8″**	0.8″	0.8″	0.9″	1.0″	1.1″
For Common Ramsden Eyepieces (to give 40° Apparent Fields)	Focus of eyepiece	1.71″	**1.71″**	1.71″	1.71″	**1.14″**	1.14″	1.14″	1.29″	1.43″	1.57″
	Focus of each lens	2.28″	**2.28″**	2.28″	2.28″	**1.52″**	1.52″	1.52″	1.72″	1.91″	2.09″
	Field lens' distance from main image	0.57″	**0.57″**	0.57″	0.57″	**0.38″**	0.38″	0.38″	0.43″	0.48″	0.52″
	Diameter of the field lens	1.36″	**1.34″**	1.34″	1.33″	**0.92″**	0.92″	0.91″	1.01″	1.11″	1.21″
	Distance of the lenses apart	1.52″	**1.52″**	1.52″	1.52″	**1.01″**	1.01″	1.01″	1.15″	1.27″	1.40″
	Diameter of the eye lens	0.87″	**0.83″**	0.82″	0.79″	**0.62″**	0.61″	0.61″	0.63″	0.66″	0.69″
	Distance of eye's pupil behind eye lens	0.81″	**0.75″**	0.74″	0.69″	**0.46″**	0.45″	0.44″	0.47″	0.52″	0.55″
Flats of Reflectors (to serve 40° apparent fields)	Distance of flat inside focus (assumed half the aperture)					**2.0″**	2.5″	3.0″	4.0″	5.0″	6.0″
	Minor Axis of Flat					**1.20″**	1.33″	1.45″	1.69″	1.90″	2.09″
	Major Axis of Flat					**1.70″**	1.88″	2.05″	2.40″	2.69″	2.95″
	Widening of tube's internal diameter to be 1″ in—					**20″**	25″	30″	40″	50″	60″
	m = Probable star magnitude	10.3	**11.0**	11.2	11.8	**11.5**	12.0	12.4	13.0	13.5	13.9
	Δ = Probable star density	13.2	**25.4**	30.3	52.7	**38.1**	59.4	84.5	142	209	283
	N = Probable stars in field	338	**345**	344	337	**244**	243	241	228	215	203

tively, and especially near the 11th magnitude, they can be obtained from the close-fitting empirical formula $\log \Delta m = (M/1.426 - 4.675 - M^2/73.6)$. The number of stars per average 40° field is then given by $N = 102.6 \times \Delta m/a$, where 102.6 is the 1257 square degrees of the apparent field divided by 3.5 squared.

The 2¾″ and the 4″ are *the* R.F.Ts for refractors and reflectors, respectively. In the special case of the reflector, the aperture to see the 11th magnitude stars is increased to nearly 4″ by the loss of light in the two reflections and by the flat's obstruction. But, then, a 1 percent further increase in aperture area results in *more* than 1 percent increase in light transmission, because of reduced flat obstruction with increase of telescopic size. That helps to sustain the number of stars appearing in the field, so that, for reflectors, *the* R.F.T. is nearer the *11.5* magnitude telescope, and that is usually of about 4″ aperture, or a little larger. Of course that 4″ reflector does not show so crowded a field as the 2¾″ refractor. The stars go down in the aperture- or field-area ratio of $(2.75/4.0)^2$, and up in the actual star-density or Δ ratio of 38.1/25.4, and therefore down in the net product-ratio of about 4 : 3.

[Editor's Note: Acquiring a 2¾″ O.G. of about $f/6$ may prove to be a problem. A cheap one will be of little satisfaction. As Mr. Walkden states it, "An indifferent O.G. makes the observer lose the tiny, needle-like points of the powdery background of faint stars." If one can write the necessary check a telescope of about R.F.T. specifications, or at least a short-focus O.G., may of course be purchased. Bausch and Lomb list a prismatic spotting scope, with 50 mm. O.G. and 3.9 mm. exit pupil, and Ottway lists a 2.1″ star, nova and comet finder, x 8, at about $26, but both are rather small. Zeiss lists a 3⅛″ comet finder with 7.5 mm. exit pupil, x 12, at $775.50—both of these including tripods, and as of 1936. Zeiss lists a 3¼″, $f/6$, two-lens O.G. at $90.75 (1936). These prices are stated in order to give a general idea of costs involved if the objective is purchased. Horace H. Selby, in a private communication, says: "Regarding a 3″, $f/6$ O.G. for R.F.T., an objective such as this can be made as a triplet, but so many sacrifices must be made that results will be disappointing at high powers if also used with them. Excellent results can be obtained with a four-element, Petzval job, however. Each job is different—different glass—and so, for best results, each job should be individually computed. A solution would be to give a specification sheet such as the one appended, suggest that the worker make up the system 'as is,' then achromatize by separating the fifth and sixth surfaces, and then clear up spherical residuals by figuring surfaces 1 and 3 as equally as possible. This procedure will yield a fair job. The glasses are cheap and durable and the system can be worked to an aperture ratio of 1:4.5. I use a 3½″ homemade on my triplet, giving a total magnification of $\times$ 9.16. Also, a 1″ ocular with my 15″, $f/3.5$ astrographic gives the most inspiring sight at $\times$ 15 that I have ever seen."

His specifications for the objective mentioned above, are shown in Figure 1.



10 Cm. E. F. Aperture ratio 1:6.0

Crown:	n_d 1.517	v 64.5
Flint:	1.573	v 42.5

Radius	Thick.	Medium
1 + 5.62 cm.	.475 cm.	Crown
2 − 4.10	.069	Flint
3 + 37.65	3.194	Air
4 + 10.00	.078	Flint
5 + 3.75	.2 to 1.0	Air
6 + 4.85	.403	Crown
7 − 19.00		

FIGURE 1

"I have recommended this four-lens objective, carefully figured, because the amateur will want to use high-power oculars with the R.F.T. from time to time. However, if only the 7 mm. exit pupil is to be used, an R.F.T. can be made, which will give fair results, as follows: B. and L. Huygens eyepiece, 38 mm, with B. and L. objective, 313 mm, *f*/5, the two costing about $25; or a Zeiss aplanat, 6x, with Fuess' achromat 510 mm *f*/5.7, these two costing about $45 (1936)."

Mr. Walkden's discussion is next resumed.]

Your comment, that beginners over-emphasize magnification, is very much the idea, and is the foundation of what I thought might some day start a growing crusade in amateur astronomy. It has long appeared to me that amateur astronomy is too much obsessed with the idea that a telescope is to be valued as a powerful magnifying instrument, with light-grasp as a secondary necessity. But for the chief pleasures in the contemplation of the sidereal heavens the telescope needs considering primarily as a light-gathering instrument, with magnifying power as the secondary necessity only so far as without some (about 3.5 per inch of aperture) the light-grasp cannot be made available. If we knew a way of increasing light-grasp without any magnification at all we should obtain most magnificent impressions of the night sky—such as possibly the owls tend to have—but, unfortunately, present optics can tell no way of having that. Photography, with its cumulative effect, is some solution of the problem, but, except in its wealth of detail, a photograph is a poor substitute for the life and sparkle of the visual impression. But the sort of instrument Mr. Tombaugh has made [See the next item —a personal communication to the writer which was seen by Mr. Walkden.—*Ed.*] is the next best thing. On the wall before me as I write hang two framed photos, one of the Andromeda Nebula and the other of the America

Nebula, and I know the R.F.T. is showing him those objects nearly like these photos; not dead, though, but come to life, so that, indeed, the solemn thinking and realizing observer can sometimes almost want to be left alone with what he sees.

[EDITOR'S NOTE: Clyde Tombaugh, the amateur telescope maker who, after building two telescopes in 1926 from the instructions given in "A.T.M.," went from his father's farm in Kansas to Lowell Observatory, secured a position there and soon became the finder of the image of Pluto on a patrol plate, later made a telescope which rates as an R.F.T. In January, 1935, he wrote the following letter, which is reproduced here to show the possibilities

FIGURE 2

Clyde Tombaugh and his two 5" telescopes—long and short. The short one is on a universal, self-adjusting Tombaugh mounting.

of the R.F.T. It would appear that Mr. Tombaugh had hit on the R.F.T. independently at about this time.]

I enclose a snapshot of my two 5" reflectors (Figure 2). The long focus 5" has a focal length of 75". Then, for the other 5", I went to the other extreme; it has a focal length of 20" ($f/4$). This was designed for star-fields, star-clusters and nebulae, and its performance has actually exceeded my best expectations and dreams. The short focal length makes for a large field of view and an intense image. By tucking it under the arm, as shown in the picture, and putting my eye to the eyepiece, I can scan the heavens with the greatest comfort. Though it uses a power of 14 diameters, I find it easier to hold steady than an 8-power binocular. The rays of light are intercepted by the flat only 3½" inside of the focus, in order to keep the diagonal as small as possible because of the steep cone. This restricts me to low-powered positive eyepieces.

The sights through this instrument are truly marvelous, especially at Flagstaff when the night sky is very transparent. The "double dark hole" or dark nebulae in Sagittarius stands out beautifully, as it does on a moderate exposure photograph. Doubtless, the strong effect is partly due to the fact that the rich star-cloud wisp in its vicinity is resolved into stars in my 5", and the absence of stars renders the dark hole conspicuous. The one faint star in this hole is easy to see. The Lagoon nebula in Sagittarius shows up well too. The dark lanes cutting through it are plainly seen. The Trifid nebula, on the other hand, is but a ghost. Since the Trifid shows up strongly on photographs, it is reasonable to infer that it is bluish, and the Lagoon nebula more yellowish. The real Sagittarius cloud of course is somewhat disappointing because it is too far away to be resolved.

Perhaps the most beautiful and richest star-fields to be found for an instrument of this size is in the Cygnus region. Much of this region is resolved into stars, and I have found some spots to run as high as 600 or 700 stars per field of view. It is a superb sight! Almost any place in this region will have 250 stars per field—the field of view being 2° in diameter. One of the astounding things is the way this type of instrument shows up the North America nebula in Cygnus. The object just about fits the field of view. The "Florida" and "Mexico" contrast well against the dark "Gulf of Mexico." The dark hole representing the "Hudson Bay" shows up conspicuously. I have easily traced the Andromeda nebula for a full degree on either side of the nucleus. The galactic star clusters are beauties, but the globular star clusters are not so good—simply an amorphous nebulosity because their stars are too faint to be resolved.

Another favorite eyepiece that I frequently use is one that gives a power of 27, and gives a field of view of nearly 1½° in diameter.

Not only the members of the Lowell Observatory, but visiting astronomers as well, have enjoyed looking through the short-focus 5" and can vouchsafe the sights described.

But all the pleasure of looking through the short-focus 5" was not confined to sweeping the heavens. The way the colored rocks (especially the red ones) showed up out on the Painted Desert, or scanning mountain scenery, is indeed a gratifying sensation. The telescope is especially useful in examining in detail the structures down in the Grand Canyon. Nor does one have to wait until toward twilight to see the mountains on the moon.

Of course, one cannot use as low a power on a short focus as on a longer one, since there is a limit to the size of the beam emerging from the eyepiece which the eye can intercept. Nevertheless one has a compact instrument for the light power, and the experiment has been a grand success.

Very recently I traded my 1" Huygenian eyepiece for a 1" Ramsden, and the results obtained with it are such that I must comment on it. The Ramsden has a very wide angle of view, and with a power of 20, gives a good field of view of two full degrees in diameter. I had to ream out the hole in the cap to permit an exit of 7 mm., so as to get the full benefit of the mirror. The

performance is most excellent, giving even better star fields and brighter nebulosities than before. A magnification of 20 is just about right (5″ mirror, ¼″ eye pupil) for the maximum effect.

Actual experiments certainly seem to substantiate the principles as given by Mr. Walkden. It was for these reasons that I attempted the short-focus reflector. My choice of a 5″ was in consideration of portability, the decreasing star ratio which is quite marked beyond the 11th magnitude, the angles subtended by galactic "open-type" star clusters and the larger nebulae, and the fact that the field of view is large enough to pick up faint objects without excessive, tedious sweeping. It is also astonishing the way the instrument shows up terrestrial objects and landscapes in rather dim twilight. But the telescope is unsatisfactory for planetary details.

[EDITOR'S NOTE: In his final sentence Mr. Tombaugh states that the R.F.T. type of telescope is unsatisfactory for planetary details, and we digress here in order to clear away that point, else some may otherwise be disappointed, following on undue expectations. The reader is referred to the chapter on "Limitations of Vision with a Telescope," by Dall, where it is similarly pointed out that, for resolving fine detail, which is the case with planetary observing, a small eyebeam or exit pupil is superior. Perhaps the following quotations, taken from personal communications, will make this matter clearer. "In a dull light, such as evening or dark, the pupil expands to 7 or 8 mm. In these circumstances a Ramsden disk of 7 mm. can be made use of. From the point of image detail, however, the resolving power of the eye reaches its limit with a pupil of 3 to 4 mm., as at this point the retinal rods and cones have dimensions at least as large as the separating power of the aperture, even with perfect sight." And again: "Two distinct properties are considered. (1) Illumination of image. This is purely a function of the Ramsden disk size, or that part which enters the pupil. (2) The resolvable detail in the image or, if you prefer, the fineness of texture of the image. Resolvable detail is not concerned with illumination. Supposing, for example, a perfect telescope is used for a bright landscape, then the retinal image will be no more crowded with detail in a 6″ telescope, power 20 (7.6 mm. Ramsden disk), than it will be with a 3″ telescope, power 20, giving a 3.0 mm. Ramsden disk. Item (1) is the only one concerned in the question of R.F.T. I entirely agree with Mr. Tombaugh's 5″, × 20 as a sound proposition for R.F.T. A reduction of power to × 17 would, however, improve matters, providing the flat is large enough to accommodate the large angular field from the mirror. This is where the refractor scores for richest-field work; there is no central obstruction, yet even the extreme edges of the field of view get the same illumination as the center."

Now to take up in detail another corner of the subject: In designing an R.F.T. it is necessary to know the diameter of the human pupil in the dark, and this was long ago stated to be one-fifth of an inch. That statement was passed along from writer to writer—none of whom apparently gave it an actual test—until it actually came to be regarded as true. In a similar man-

ner mistakes, once embodied in textbooks and encyclopedias—especially the latter—have often been passed down from decade to decade, copied into other textbooks and encyclopedias, and carried along until they acquired prestige due to sheer longevity. Such was the case with the venerable pupilar diameter dogma until about 1916, when its accuracy was questioned and several investigations of the real pupillary diameter were carried on. With his kind permission and that of the publishers, an article of that time, by W. H. Steavenson, F.R.A.S., a widely known English variable star observer with much practical experience, is here reprinted from the *Journal of the British Astronomical Association,* Vol. 26 (1916), page 302.]

Note on Low Powers, W. H. Steavenson, 1916: Nearly every text-book dealing with the practical side of astronomy contains the familiar statement that the lowest power which can usefully be employed on any telescope is one of 5 to each inch of aperture. This statement is, of course, based on the assumption that the average diameter of the human pupil is one-fifth of an inch. It is impossible to find out how the adoption of this value originated, but it was presumably the outcome of an inquiry addressed by some astronomer to one of his physiological friends. If this was so, it is somewhat unfortunate that the physiologist omitted to mention that the value given was only a *daylight* average. As such it is, no doubt, very fairly correct, but it obviously has no useful application to the astronomical telescope, which is used almost entirely at night. The question which really concerns the astronomer is—what is the average diameter of the pupil under ordinary observing conditions, *i.e.,* in semi-darkness.

It will be obvious that no direct measure of this amount can readily be made, since any light strong enough to render the pupil clearly visible would also destroy the value of the measures by causing it to contract. So far as I could see, the only reliable method was to make an instantaneous photograph of the eye in darkness by flashlight, and then measure the image on the plate. The success of a preliminary experiment on these lines encouraged me to take a series of these photographs, with a view to arriving at a fair mean value for the diameter of the pupil. In my subsequent experiments I had the kind assistance of several gentlemen at Guy's Hospital, who allowed me to photograph their eyes. The latter may, I think, be fairly regarded as normal, their owners being between 21 and 25 years of age and, so far as I know, in perfect health. I had at first intended to take a mean of ten cases, but the close agreement between the first five measures suggested that this would be unnecessary. In the room in which the photographs were taken there was, perhaps, rather more light than in the open air on a star-lit night. In each case the subject's eye was allowed to rest in this semi-darkness for about ten minutes before being photographed, and at the actual time of exposure was focussed on a distant object in order to avoid the contraction of pupil which might otherwise have been caused by the proximity of the camera lens.

My results were as follows:

Subject	Iris	Pupil		Ratio I:P	
C. C. B.	.58 ins.	.35 ins.	Mean .336 ins.	1.66	Mean 1.54
W. H. G.	.50 "	.33 "		1.51	
A. S. P.	.53 "	.34 "		1.53	
H. O. L.	.49 "	.32 "		1.53	
E. R. W.	.50 "	.34 "		1.47	

It will be seen that the mean value of the diameter of the pupil comes to just over one-third of an inch, and this may, I think, be confidently accepted as the average night aperture of the eye. No doubt the pupil would contract a good deal more during the observation of a very bright star, but, since very low powers are generally used on faint objects only, this does not affect the question materially. Individual peculiarities may increase the minimum power from 3 to 3.5, or even perhaps 4, per inch, but 5 is certainly beyond the mark, and it is to be hoped that the inaccurate and unverified statement which prompted the writing of this paper will not continue to be slavishly copied by the writer of every text-book.

A note, added 1936, in a personal communication to the editor: "If I were to rewrite that paper, I should modify my statement that one-fifth inch was a daylight value, as this is clearly too high. The term 'daylight' is obviously a variable quantity, depending on the brightness of the day and the location of the observer. Out in the open on a sunny day, with the eye itself shielded from the sun, one-tenth or one-twelfth inch would probably be a more accurate figure. One-fifth inch might be taken as a twilight average. But my real point was that the true *night* value was considerably greater.

"For measurement, a scale was photographed in the same plane as the pupil, and measures of the iris, both on the plate and the subject, provided a check."

[EDITOR'S NOTE: Those who wish to follow up this interesting subject are referred to an article by Prentice Reeves, a psychologist, in *Astrophysical Journal,* Vol. 46, page 170. He pasted a millimeter scale in a vertical position near the eye (between the eye and the nose) and in the same plane as the pupil, seated the subject near the camera, in order to get a large image and, after waiting for dark adaptation, took flashlight pictures. He states his belief that the diameter of the eye is not constant, fluctuating from time to time. For his own pupil he obtained an average of 8.3 mm. An article by the same author, in *Psychological Review,* Vol. 25 (1918), pages 330–340, shows photographs of numerous persons' eyes with the scale attached nearby. A commentary on this and two other papers bearing on the subject appeared in the *Journal of the British Astronomical Association,* Vol. 28, page 135.

So much attention given to so small a matter as the pupilar opening may perhaps seem superfluous, until it is realized that the user's eye is as much a part of the R.F.T. as its objective or eyepiece, and quite as important. Prof. Henry Norris Russell, in the *Astrophysical Journal,* Vol. 45, page 61,

mentions that a one-third inch pupilar opening has nearly three times the area of a one-fifth inch opening, an added reason why small measurements here are quite important—small differences in pupilar opening effect large changes in R.F.T. design.

While the pupil opens, as Dr. Steavenson has shown, to just over one-third inch, he points out in a personal communication that "if the power be lowered until a Ramsden disk of .33″ is obtained, the increased brightness of the sky background would almost certainly tend to diminish this full aperture of the pupil, so that a compromise would probably be reached at a disk of something nearer .25″ to .30″." This is about the amount that is accepted by most modern designers as optimum.

Ainslie, in "The Splendour of the Heavens," page 753, suggests that perhaps older eyes—those of middle-aged persons—may not show so large a pupilar opening as those of younger persons, but Steavenson suggests that experimental evidence would be desirable here; perhaps some reader will do further research on this question.

The R.F.T. pretty closely matches requirements for meteor observation, contained in several communications received from Prof. C. C. Wylie, President of the Mid-West Meteor Society and head of the Department of Mathematics and Astronomy at the State University of Iowa, Iowa City, Iowa. One of these reads: "I have been wondering whether some of the amateur telescope makers would be willing to make counts of meteors, using wide-field and low-power eyepieces. The eyepieces should have a magnification of 4 or 5 to the inch, and a good field of view equivalent to 50° with the naked eye. For example, an aperture of 4″ should have a power of between 16 and 20, and a field of view of between 2½° and 3°. We need these counts to give better numbers on meteors too faint to be seen with the naked eye."

Another reads: "For some meteor work small telescopes or monoculars of 2″ or 3″ aperture would be very useful. If made on a short focal ratio, let us say F-4 and with wide-field eyepieces, these would be excellent for the plotting of telescopic meteors near the radiant. The usual telescopes of 2″ or 3″ aperture are of such a long focal ratio that, to cover a reasonable field and have good light-gathering power, the field lens of the eyepiece would have to be as large as the objective or even larger. It seems to me that a chapter on short-focus refracting instruments would add to the interest of many in your book. Some of the most interesting work is that of Dr. Poulter in the Antartic, using binocular night glasses with a field of about 7° and a power of 4½.

"Some experiments on the diameter of the pupil have been carried on by the psychology department here. They agree with the results of Steavenson, and with some work at the Eastman Kodak Company, in indicating that the diameter of the pupil may be as much as ⅓″ in relatively complete darkness. This indicates that the power might perhaps be as low as 3 to the inch, and that certainly 4 to the inch would be better than 5 to the inch, if a person is working on a clear moonless night and well away from artificial light."

What about the R.F.T. regarded as a comet seeker? It can be used for

that work, though higher powers in combination with the low ones of an R.F.T. are generally used. Zeiss offers a comet seeker described as a 3.20" refractor with magnifications × 12, × 20, × 27, and × 39, and another described as an 8" with × 27, × 44, × 74, × 106, and × 265. The comet discoverer L. C. Peltier writes, in reply to an inquiry, "My instrument (Figure 3) has a focal length of 48" and I find that a magnification of × 25 gives me the best results in comet seeking. My eyepiece has a field lens diameter of 1¾" and gives a field 2° in diameter. Less magnification than this would fail to show the nebulous appearance of a faint comet and it would appear as an ordinary star. On the other hand, a magnification much greater than 25 would seriously affect the efficiency of the instrument by cutting down the field diameter. I find that two oculars are ample for all my work—the × 25 for spotting any nebulous object and a × 60 for detailed examination."

In sum, then, when designing an R.F.T. of a certain chosen aperture, a start is made with the observer's pupillar opening. This is either assumed to be some average amount, like 2/7", the equivalent of .286", or actually measured.

Second, the focal lengths of objective and eyepiece are chosen at such "gear ratio" that the exit pupil will have the desired diameter,[5] equaling the pupilar opening.

When the telescope is a reflector of moderate aperture up to about 12", not only should the "gear ratio" be right, but the length of the telescope should be about 4 to 5 times the aperture. That is advisable in order to keep the flat from being large and covering up too much of the mirror.

When for good and scientific reasons the observer wants his own *the* R.F.T., or what may here be called his own Richest Richest-Field Telescope of the most crowded possible average field, the start is made with that aperture which will reveal to him stars of the magnitude at which star density increase at 2½ times per magnitude—2.4 times for a reflector. This will vary with other factors, such as the condition of seeing and the keenness of the observer's sight,[6] but in many cases may be assumed to be a

[5] The diameter of the objective is to that of the exit pupil as the focal length of the objective is to that of the eyepiece. But it should not always be assumed that the *e.f.l.* that is neatly stamped on a given eyepiece is exact; often the amount is "nominal."

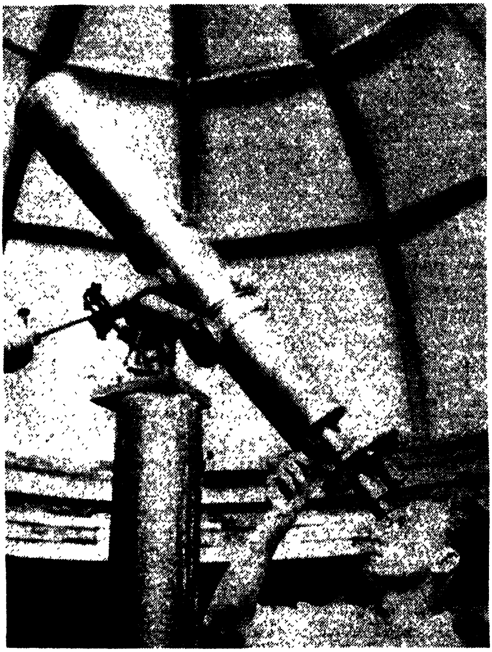
[6] "You note that a star of the 13th magnitude requires a 6" glass, whereas I can often see 14th magnitude stars with my 6."—Personal communication from L. C. Peltier. Comment by Mr. Walkden:

"The seeing 14th magnitude stars with 6" aperture much astonishes me. A straight line drawn on a sheet of logarithmic paper before me tells that such eyes must see stars of nearly magnitude 7½ without a telescope, so as to make the night sky be a positively glittering sight compared with what it is to the average person. That person hardly notices stars fainter than the 5th magnitude, and most of the keenest sights, I thought, failed to detect at about 6¼ magnitude. For Mr. Peltier the R.F.T. should be as small as about 1.5" aperture, and the average Milky-Way view show up nearly 2000 stars!"

A table in Bell, "The Telescope," gives, for 1" aperture, minimum visible, 9th magnitude; for 3", 11th magnitude; for 6", 13th magnitude; for 10", 14th magnitude. Two of these four points may be said to be on the logarithmic straight line passing through 1" aperture for the 9th magnitude, and 10" aperture for the 14th magnitude. The other two points are not on the straight line, though they may be said to be as near as round, whole figures permit. The figures, of course, vary to some extent for different observers.

little under 3″ aperture for a refractor—a little under 4½″ aperture for a reflector.

In this little summary magnification has not been mentioned, but this it is not necessary to know. However, since it is interesting to know, it may be derived by dividing the focal length of the objective by the *e.f.l.* of the eyepiece.



Science Service photo

FIGURE 3

L. C. Peltier, of Delphos, Ohio, and his comet-seeker. According to a note in Popular Astronomy, he has considerably better than average eyesight. He also makes use of this gift by devoting thousands of hours of his time to science.

The magnification is, however, only an incidental thing. The main thing is to hook up the objective and eyepiece at the correct "gear ratio" to bring the exit pupil out at the correct diameter. This point may seem a quibble or a distinction without a difference, and of course it is not important whether we think in direct terms of gear ratio or of gear ratio worked out to a quotient, that is, magnification. There is, however, some odd quirk in our mental processes whereby we often seem to think more easily in an indirect manner than in a direct one—by way of some derived concept instead of the

original one—so let us, if we prefer, have it in the derived terms of magnification.

A thoughtful man once pointed out how this same illogical quirk in human mental processes might be taken advantage of to save the present writer about six months of night and holiday hard work. During the previous years a few readers had suggested that he ought to melt up and recast "A.T.M." in a better organized mold, so that it would march straight through the work of mirror making, followed by accessory making, in a logical manner, and no longer be arranged as it stands, that is, all over the lot, inside out and hind side before—due, of course, to the fact that the book grew, through a period of years, by accretions each of which added a fresh wave of material. The man mentioned above asserted that the correct arrangement of the book was just as it is, and the reason he gave was that this corresponds to the usual method of human thinking. It doubtless is a fact that we seldom plan a day's events or an itinerary, solve a problem, work out a story plot, make an invention or acquire a new art, straight through from logical beginning to logical end. Instead, we think things out in sections, not necessarily in sequence, and then as we become familiar with a subject we juggle these sections around in our minds until, like a picture puzzle, the logical sequence finally takes form out of the void. Designing a telescope is something like that.

Moreover, it may be true, as has often been pointed out, that the harder the tyro has to perspire over "A.T.M." the better he will nail down its content. This is well known to be the fiendish basis on which some textbooks are prepared—for example, those of mathematics. Furthermore, frequently making and then remaking books about telescope making has the drawback that it leaves the maker of telescope books no time to make telescopes.

Hence the man alluded to above—bless his heart—said that, even if the editor were to go to the trouble of rearranging "A.T.M." in a seemingly logical sequence—more of a job than it may seem to be at first glance—the readers might then find it actually necessary to turn themselves inside out in order to absorb its contents in a normal manner, just as the mirror image of a reversed image is normal. And if a lot of tyros were forced to resort to so risky a procedure as this, they might end up in a horrible predicament—stuck in the middle—and be unable to move one way or t'other, as depicted by Russell W. Porter in the tailpiece.]

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